

# **TROPOSPHERIC EMISSION SPECTROMETER (TES)**

## **LEVEL 2 ALGORITHM THEORETICAL BASIS DOCUMENT APPENDIX**

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## APPENDICES

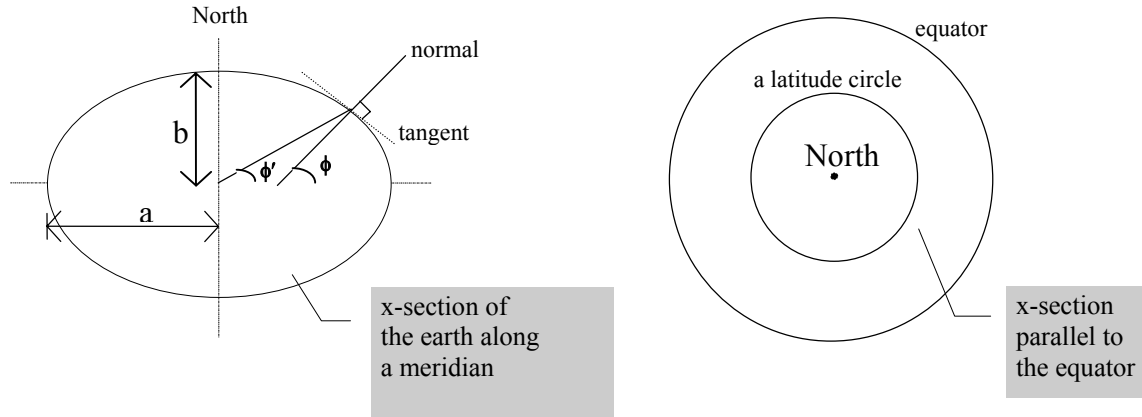
### A3.3.1: Radiative Transfer

The Radius of Curvature of the Earth's Surface for a Given TES Limb Tangent Latitude and Viewing Direction

The ray-tracing step in Level 2 process uses Snell's Law for a spherically symmetric atmosphere to determine the bending along the ray. The radius of the "sphere" is considered to be the sum of the altitude and the *radius of curvature of the Earth surface* (not the Earth-centered radius) at the given location in the given direction. This Appendix presents the equations for the radius of the Earth surface curvature at a given latitude (TES limb tangent latitude) for TES viewing direction.

A very commonly used Earth geometric model is an ellipsoidal shape as illustrated below.

**Figure A-1: Earth Geometric Model**



Definitions of some parameters:

- $a$  — equatorial radius (the semi-major axis of the meridian ellipse).
- $b$  — polar radius (the semi-minor axis of the meridian ellipse).
- $f$  — flattening factor.
- $e$  — Earth ellipsoid eccentricity.
- $\phi$  — geodetic latitude as illustrated above.
- $\phi'$  — geocentric latitude as illustrated above.

Their relationships:

$$\tan(\phi) = \frac{\tan(\phi')}{(1-f)^2}; \quad (\text{A.1})$$



$$f = \frac{a-b}{a}; \text{ and} \quad (\text{A.2})$$

$$e = \sqrt{2f - f^2}. \quad (\text{A.3})$$

There are two principle curvatures on the model Earth surface at a given location, the meridian curvature (North-South curvature) and the East-West curvature. The tangents of these two curvature are perpendicular. The East-West curvature plane is defined by the tangent along a latitude circle and the local normal. The equations for the radius of these two principle curvature planes are:

Radius of curvature in the North-South plane:

$$R_{NS} = \frac{a(1-e^2)}{(1-e^2 \sin^2 \phi)^{3/2}}. \quad (\text{A.4})$$

Radius of curvature in the East-West plane:

$$R_{EW} = \frac{a}{(1-e^2 \sin^2 \phi)^{1/2}}. \quad (\text{A.5})$$

TES always looks straight backward along the orbit. The orbit has 98.21° inclination angle which is the angle between the equatorial plane and the orbital plane. The parameter to define the TES viewing direction at its limb tangent point or any point along its line of sight is the azimuth angle ( $A_z$ ). The azimuth angle is the angle between the local meridian plane (the N-S plane) and the plane defined by the local normal and the tangent along the TES viewing direction. Under the spherical approximation,  $A_z$  can be calculated as

$$\sin(A_z) = \frac{\cos(\text{inclination\_angle})}{\cos(\text{geocentric\_latitude}, \phi')}. \quad (\text{A.6})$$

The EOS Toolkit provides a program to calculate a more rigorous azimuth without the spherical approximation (PGS\_CSC\_ZenithAzimuth). The viewing vector however, in the ECR (Earth Centered Rotating) coordinate system, needs to be defined.

The radius of the curvature in azimuth  $A_z$  ( $R_C$ ) can be calculated as

Radius of curvature in azimuth  $A_z$ :

$$\frac{1}{R_C} = \frac{\cos^2(A_z)}{R_{NS}} + \frac{\sin^2(A_z)}{R_{EW}}. \quad (\text{A.7})$$

### **A3.3.1.1: Ray Tracing and Path Integrals**

For ray tracing and path integrals, we require the following elements from the retrieval vector, at a set of levels  $j=0..n$  in  $\ln(P)$ , and in the limb case when the atmosphere is not horizontally homogeneous, also at a set of locations along the line of sight:

$T_j$	level temperatures
$q_{jm}$	level mixing ratios for molecule m
$P_s$	surface pressure
$T_s$	surface temperature

and the following forward model parameters:

$z_s$	altitude of the surface relative to the geoid
$R_c$	radius of the geoid at the measurement location
$R_{cs}$	altitude of the spacecraft from the center of curvature of the geoid
$\theta_s$	angle of ray at the satellite

The level quantities in the retrieval vector are interpolated at a finer spacing to give the full grid level values  $q_k^m$  and  $T_k$ .

#### **A3.3.1.1.1 Hydrostatic Equation**

The total air density  $\rho_k$  is computed from the gas equation at each full grid level. This must allow for the water content of the air, but the other minor constituents may be ignored [except possibly CO<sub>2</sub>] (see Appendix 3.3.1.1.7). The hydrostatic equation may be written

$$dz = -[P/\rho(P)g(z)] d \ln(P) \quad (\text{A.8})$$

As the quantity  $[P/\rho(z)g(z)]$  is close to  $RT/Mg$ , from the ideal gas equation, we take it to be linear in  $\ln(P)$  over each layer. Hence the layer thickness is

$$z_k - z_{k-1} = (P_{k-1}/r_{k-1}g_{k-1} + P_k/\rho_k g_k)[\ln(P_{k-1}) - \ln(P_k)]/2 \quad (\text{A.9})$$

from the trapezoidal rule. The acceleration due to gravity is given as a function of height and latitude, and it consists of gravitational and rotational parts,

$$g(\phi, z) = g_{\text{grav}}(\phi, 0)[(R_e)/(R_e + z)]^2 - \Omega^2 N[(N+z)/R_e \cos \phi]^2 \quad (\text{A.10})$$

where  $\Omega$  is the Earth's rotational angular frequency;  $N = a^2 \sqrt{(a^2 - (a^2 - b^2) \sin^2 \phi)}$ ; and  $a$  and  $b$  is the semi-major and minor axis of earth respectively. The gravitational term at the earth surface is given by [International Gravity Formula, 1980]

$$g(\phi, 0) = 978.0327(1.0 + 0.0052790414 \sin^2 \phi + 0.0000232718 \sin^4 \phi + 0.0000001262 \sin^6 \phi) \quad (\text{A.11})$$

and,

$$g_{\text{grav}}(\phi, 0) = g(\phi, 0) - g_{\text{rot}}(\phi, 0). \quad (\text{A.12})$$

Note that equation (A.12) requires  $g_k = g(z_k)$  before  $z_k$  has been computed. The effect is small and can be accommodated by several different ways, of which the simplest might be to approximate  $g_k$  by its value at an altitude given by  $2z_{k-1} - z_{k-2}$ .

#### ***A3.3.1.1.2 Ray tracing in the nadir case.***

The zenith angle of the ray at each level is given by Snell's law in spherical symmetry:

$$\sin \theta_k = [R_{cs} \sin \theta_s] / [(R_c + z_k) n_k] \quad (\text{A.13})$$

where the refractive index  $n_k$  is given in section A3.3.1.1.8. However as  $n_k \sim 1.0002$  at the surface, it may be ignored, incurring an error of only 0.02% in  $\sin \theta_k$ , and hence a similarly small amount in path length through  $\sec \theta_k$ .

#### ***A3.3.1.1.3 Path integrals in the nadir case***

We need to evaluate the number of molecules per unit area in each layer, together with appropriately weighted mean pressures and temperatures of the layer. The mass per unit area of an element  $dP$  is  $dP/g$ , so the number of molecules of molecule  $m$  is

$$dn_m = N q_m dP / g [M_d + q^w M_w] \quad (\text{A.14})$$

where  $N$  is Avogadro's number,  $q_m$  is the volume mixing ratio of molecule  $m$ , defined as the ratio to the number of molecules of *dry* air,  $M_d$  and  $M_w$  are the molar masses of dry air and water, and  $q^w$  is the mixing ratio of water vapor. Hence the number of molecules of  $m$  in a layer along the line of sight is

$$u_{lm} = \int_{l_{l-1}}^l q_m(P) f(P) dP \quad (\text{A.15})$$

where

$$f(P) = \sec \theta N / g [M_d + q^w M_w] \quad (\text{A.16})$$

is very nearly constant over a layer. Interpolating  $\ln(f)$  as well as  $\ln(q_m)$  linearly in  $\ln(P)$ , we obtain integrals that can be evaluated analytically. Putting

$$q_m f = q_{ml-1} f_{l-1} (P / P_{l-1})^{\alpha_l} \quad (\text{A.17})$$

within the layer, where  $\alpha_l = \ln(q_{ml} f_l / q_{ml-1} f_{l-1}) / (\zeta_l - \zeta_{l-1})$ , we obtain

$$\begin{aligned} u_{lm} &= [q_{ml-1} f_{l-1} P_{l-1} - q_{ml} f_l P_l] / (1 + \alpha_l) \\ &= q_{ml-1} f_{l-1} P_{l-1} (\zeta_l - \zeta_{l-1}) E[(1 + \alpha_l)(\zeta_l - \zeta_{l-1})] \end{aligned} \quad (\text{A.18})$$

where  $E(x) = [1 - \exp(-x)]/x$ , which will need special evaluation near  $x=0$ . The first form is simpler, but the second form is needed when  $(1 + \alpha_l) \sim 0$ . We also require the weighted mean pressure and temperature obtained from

$$u_{lm} \bar{P}_l = - \int_{l_{l-1}} l_{l-1} q_m f P \, dP \quad (\text{A.19})$$

$$u_{lm} \bar{T}_l = - \int_{l_{l-1}} l_{l-1} q_m f T \, dP \quad (\text{A.20})$$

in order to evaluate the optical depth

$$\tau_v = k_v(\bar{P}, \bar{T}) u \quad (\text{A.21})$$

where  $k_v$  is the absorption coefficient (cross section) to be interpolated from a tabulation against pressure and temperature. We easily obtain

$$\begin{aligned} u_{lm} \bar{P}_l &= [q_{ml-1} f_{l-1} P_{l-1}^2 - q_{ml} f_l P_l^2] / (2 + \alpha_l) \\ &= q_{ml-1} f_{l-1} P_{l-1}^2 (\zeta_l - \zeta_{l-1}) E[(2 + \alpha_l)(\zeta_l - \zeta_{l-1})] \end{aligned} \quad (\text{A.22})$$

The temperature integral can also be performed algebraically, but leads to slightly more complicated expressions.

For computational efficiency we wish to avoid a two dimensional interpolation in the absorption coefficient tables. The mean pressure is therefore approximated by its value at  $\alpha_l = 0$ , and the tabulation made at the corresponding set of layer mean pressures,  $\bar{P}_l = (P_l + P_{l-1})/2$ . This approximation is in error by 1.2% in pressure at  $\alpha = < 1$  for a layer thickness of 1 UARS layer, and is quadratic in layer thickness.

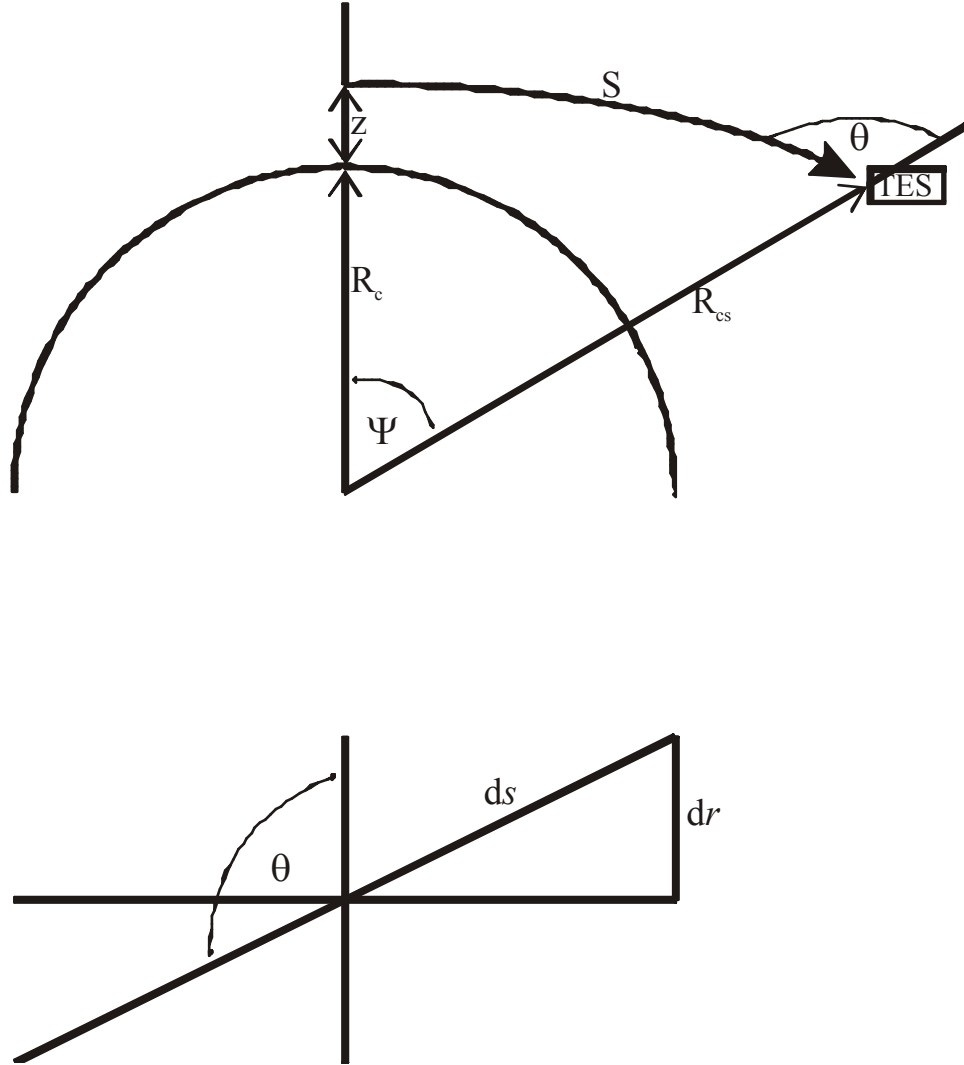
#### ***A3.3.1.1.4 Ray Tracing in the Limb Case***

To avoid a pressure interpolation in the absorption coefficient table in the forward model, we need to predetermine the layer mean pressures in order to tabulate at the required pressures. Therefore we ray trace forward from a set of tangent points on the full grid (with given pressures) and evaluate the forward model for these rays, rather than tracing from the satellite in a set of directions related to the detector array. The ray trace will provide an angle of incidence at the satellite, so that a quadrature over the field of view of each detector can be carried out.

The use of a pressure grid involves an extra complication, because ray tracing is essentially a geometric procedure, best carried out in height coordinates, while the state vector is defined in pressure coordinates. In the case when horizontal homogeneity is assumed, the approach is relatively straightforward, following the principles of the method used in Kneizys *et al.* (1983). The quantities required from the ray trace are the angle of the ray at the satellite, and the pressure

as a function of distance along the ray, so that path integrals such as  $\int q \rho \, ds$ ,  $\int q \rho P \, ds$ , and  $\int \rho T \, ds$  can be evaluated for each layer.

**Figure A-2: Propagation of a refracted ray through the limb**



First we use the hydrostatic equation to obtain the heights  $z_k$  of the pressure levels for the full grid. These will not be equally spaced in height. We then trace a ray from each  $z_k$  as tangent height to the altitude of the satellite, relative to the center of curvature of the geoid. See Figure A-2 to define the terminology. For the refracted ray in the horizontally homogeneous case, the zenith angle of the ray at any altitude can be obtained from Snell's law:

$$n(r)r \sin \theta(r) = r_m \quad (\text{A.23})$$

where  $r = z + R_c$  and  $r_g = n(r_i)r_t = R_{cs} \sin\theta_s$ , is a constant for the ray, the geometric tangent radius or the *impact parameter*. Using

$$dr = \cos\theta \, ds \quad (\text{A.24})$$

we obtain

$$ds = (1 - r_g^2/n^2 r^2)^{-1/2} \, dr \quad (\text{A.25})$$

which cannot easily be integrated numerically to obtain  $s(r)$  because of the singularity at the tangent point. However by changing the variable of integration from  $r$  to  $x = r \cos\theta$  we can obtain

$$ds = dx/[1 - \gamma(r) \sin^2\theta(r)] \quad (\text{A.26})$$

where  $\gamma = -(r/n) \partial n / \partial r$ , a positive quantity, is an explicit function of  $r$ , as is  $\sin\theta$ . The coordinate  $x$  has the property that in the absence of refraction,  $x = s$ . To integrated over each full grid layer, we choose a set of quadrature points  $x_l$  within the layer, and use e.g. the trapezium rule:

$$\Delta s = \sum_i (x_i - x_{i-1}) (1/(1 - \gamma_i \sin^2\theta_i) + 1/(1 - \gamma_{i-1} \sin^2\theta_{i-1}))/2 \quad (\text{A.27})$$

or some higher order integration rule. Note that it is not straightforward to find the altitudes of a set of points equally spaced in  $x$  because  $x^2 = r^2 - r_g^2/n^2(r)$  cannot be explicitly inverted to give  $r(x)$ , even though  $x$  can be evaluated at any given value of  $r$ . Either  $r^2(x) = x^2 + r_g^2/n^2(r)$  must be evaluated iteratively, or points chosen in  $r^2$  to make them approximately evenly spaced in  $x$ .

The refractive index of air is given in section A3.3.1.1.8 as an experimentally fitted function of pressure, temperature and water vapor. However it is close to being of the form  $n = 1 + \alpha \rho(r)$ , where  $\alpha$  is a constant, so that within each narrow layer, such as the full grid layer, it may be reasonably fitted to the form

$$n = 1 + \alpha \rho_0 \exp(-r/H_n) \quad (\text{A.28})$$

so that we can write

$$\partial n / \partial r = -(n - 1)/H_n \quad (\text{A.29})$$

where  $H_n$  is the scale height of refractivity,  $n-1$ , within the layer.

#### ***A3.3.1.1.5 Path Integrals for the Limb Case***

The absorber amount of molecule  $m$  in a sublayer,  $\Delta u_m = \int q_m \rho \, ds$  can be evaluated in the same way as  $\Delta s$  by integrating with respect to  $x$  using the trapezium (or other) rule:

$$\Delta u_m = \sum_l (x_l - x_{l-1})(q_{lm}\rho_l/(1-\gamma_l\sin^2\theta_l) + q_{ml-1}\rho_{l-1}/(1-\gamma_{l-1}\sin^2\theta_{l-1}))/2 \quad (\text{A.30})$$

The effective pressure for a full grid layer is defined by

$$\bar{P} = \int \rho P \, ds / \int \rho \, ds \quad (\text{A.31})$$

where the two integrals are evaluated as sums over sublayers within the full grid layer, the elements of the sums being

$$\int \rho P \, ds = \Delta(uP) = \sum_i (x_i - x_{i-1})(P_i\rho_i/(1-\gamma_i\sin^2\theta_i) + P_{i-1}\rho_{i-1}/(1-\gamma_{i-1}\sin^2\theta_{i-1}))/2 \quad (\text{A.32})$$

and

$$\int \rho \, ds = \Delta u = \sum_i (x_i - x_{i-1})(\rho_i/(1-\gamma_i\sin^2\theta_i) + \rho_{i-1}/(1-\gamma_{i-1}\sin^2\theta_{i-1}))/2 \quad (\text{A.33})$$

The integral over the lowest sublayers (close to the tangent point) should be evaluated using a quadratic rule.

The effective temperature for a full grid layer is defined by

$$\bar{T} = \int \rho T \, ds / \int \rho \, ds \quad (\text{A.34})$$

in a similar way to the effective pressure. The elements of the sum for the numerator are

$$\Delta(uT) = \sum_i (x_i - x_{i-1})(T_i\rho_i/(1-\gamma_i\sin^2\theta_i) + T_{i-1}\rho_{i-1}/(1-\gamma_{i-1}\sin^2\theta_{i-1}))/2 \quad (\text{A.35})$$

Again, the integral over the lowest sublayers should be evaluated using a quadratic rule.

#### ***A3.3.1.1.6 Ray tracing in the Inhomogeneous Limb Case.***

It is marginal whether the change in the refracted path due to horizontal inhomogeneities is significant. In the worst case, the slope of a pressure surface of 0.001, corresponding to a geostrophic wind of 100 m s<sup>-1</sup>, gives an error in tangent height at mid troposphere of order 40 m, or about 0.5% in pressure or density. Nevertheless we give the following analysis to describe a possible approach, should it be needed on further investigation.

In the general case the refraction equations do not have an explicit solution expressible as integrals, unlike the horizontally homogeneous case. A set of coupled ordinary differential equations can be derived, relating  $r(s)$ ,  $\theta(s)$  and  $\psi(s)$ :

$$d(\theta+\psi)/ds = -\sin\theta/n \, (\partial n/\partial r)_\psi + (\cos\theta/rn)(\partial n/\partial \psi)_r \quad (\text{A.36})$$

$$dr/ds = \cos\theta \quad (A.37)$$

$$d\psi/ds = \sin\theta/r \quad (A.38)$$

where  $\psi$  is the angle at the center of curvature relative to the instrument. The first equation states that the curvature of the ray is equal to the fractional gradient of the refractive index normal to the ray. The others are simple geometry. We can use (A.36) and (A.38) to obtain:

$$d\theta/ds = -\sin\theta[1/r + 1/n (\partial n/\partial r)_\psi] + (\cos\theta/rn)(\partial n/\partial \psi)_r \quad (A.39)$$

Equations (A.36), (A.37) and (A.38) can be integrated by any standard differential equation solver such as Runge-Kutta to give  $r(s)$ ,  $\theta(s)$  and  $\psi(s)$ .

The boundary conditions cause difficulties, however. A single ray must pass through the instrument at a known location, and have a tangent point at a given pressure level:

- (i) at  $s = 0$ ,  $\psi(0) = 0$  and  $r(0) = R_{cs}$
- (ii) at  $r=r(\zeta_i)$ ,  $\cot\theta = - (1/r)(\partial r/\partial \psi)_\zeta$ , i.e the slope of pressure surface  $\zeta_i$

where  $\zeta = -\ln(P/P_0)$ . Here I have put the origins of  $\psi$  and  $s$  at the instrument for convenience. We do not know before the ray trace where  $\psi$  of the tangent point is relative to the satellite. (This does not matter in the case of the horizontally homogeneous atmosphere.) Therefore we must solve the problem iteratively by either:

- (a) finding the value of  $\psi$  at the tangent point for which the ray passes through the instrument, or
- (b) finding the scan angle  $\theta_s$  at the satellite which gives a tangent point at the right pressure level

To locate the tangent point relative to the satellite, it is most convenient to locate the origin of  $s$  at the tangent point and the origin of  $\psi$  at the instrument. The initial conditions are, at the tangent point

$$(i) \ s = 0 \quad (ii) \ r = r_t \quad (iii) \ \psi = \psi_t \quad (iv) \ \cot\theta = -(1/r)(\partial r/\partial \psi)_\zeta.$$

Integrate forward from the tangent point until the ray reaches satellite altitude  $R_{cs}$ . The ray will miss the instrument by an amount  $\psi(R_{cs})$ . This quantity is then subtracted from  $\psi_t$  for the next iteration. If there were no line of sight gradients, we would need to go no further, but one more iteration will probably be necessary for convergence.

The temperature, water and (hence) the refractive index are specified vertically on the full grid, and horizontally at some set of values of  $\psi$ . Use the hydrostatic equation to find  $r$  on this same grid. Then the table can be used to find the partial derivatives  $(\partial n/\partial r)_\psi$ ,  $(\partial n/\partial \psi)_r$  and  $(\partial r/\partial \psi)_\zeta$  where they are required.

There is the extra complication that we want to find quadrature points along the rays lying on the full grid. We are at liberty to choose the quadrature points for the integration so we will change



them as we iterate so that a subset ends up lying on the pressure grid. The suggested process is as follows, for each full grid level within the range seen by the instrument:

Repeat:

- Select a set of quadrature points in  $s$ :
- First time round, use  $s = ih$ ,  $i=0,1..$  for some constant spacing  $h$ .
- Subsequent times we will have a reasonable guess at the ray path, so use the tangent point, plus points where the ray intersects the full grid (inverse interpolate in  $\zeta(s)$ ), subdividing sections so that no interval is longer than  $h$ .
- Adjust the initial condition  $\psi_t$
- Integrate forward & backward through the atmosphere to give  $r(s)$ ,  $\theta(s)$  and  $\psi(s)$ .
- Use a straight line ray from just outside the atmosphere where  $n=1$  to the satellite altitude to calculate the angle  $\psi_s$  by which the ray misses the instrument
- Evaluate  $\zeta(s)$  at each quadrature point (use  $r$ ,  $\psi$  to interpolate in the 2-D profile table). until converged (fixed number of times, probably 3 or 4)

Carry out the path integrals using the same quadrature points and e.g. Simpsons rule.

The fixed number of iterations is required so that we safely can do a numerical perturbation of the ray trace for the Jacobian calculation.

A reasonable initial value for  $\psi_t$  can be obtained by starting with the highest tangent point required, initialized with the geometric (unrefracted) value, and work downwards, each time using the final value for the previous level as the initial value for the current level.

We should probably check for pathological circumstances such as the ray being refracted below the tangent level, by at least checking whether  $r < r_t$ ! This applies to the homogeneous case too.

The alternative approach of finding the scan angle  $\theta_s$  at the satellite which gives a tangent point at the right pressure level turns out to be more complicated, and not worth pursuing:

#### ***A3.3.1.1.7 The gas equation for air***

The gas equation for air is given by Ciddor [1996] as

$$\rho = \frac{M_{dry}}{R^*T} p \cdot \frac{\left[ 1 - X_{H_2O} \left( 1 - \frac{M_{H_2O}}{M_{dry}} \right) \right]}{Y}, \quad (A.40)$$

where  $R^* = 8.31451 \text{ J mole}^{-1} \text{ K}^{-1}$ , the universal gas constant;

$$M_{dry} = [28.9635 + 12.011 \cdot 10^{-6} (X_{CO_2} - 400)] \cdot 10^{-3} \text{ kg/mole};$$

$$X_{CO_2} = 1.5202 \cdot q_{CO_2};$$

$$M_{H_2O} = 0.018015 \text{ kg/mole};$$

$$X_{H_2O} = 0.6223 \cdot q_{H_2O}; \text{ and}$$

the compressibility factor  $Y$  is given by

$$Y = 1 - (P/T)[a_0 + a_1 t + a_2 t^2 + (b_0 + b_1 t)X_{H_2O} + (c_0 + c_1 t)X_{H_2O}^2] + (P/T)^2(d + eX_{H_2O}^2)$$

where

$$a_0 = 1.58123e^{-6}$$

$$a_1 = 2.9331e^{-8}$$

$$a_2 = 1.1043e^{-10}$$

$$b_0 = 5.707e^{-6}$$

$$b_1 = 2.051e^{-8}$$

$$c_0 = 1.9898e^{-4}$$

$$c_1 = 2.376e^{-6}$$

$$d = 1.83e^{-11}$$

$$e = -0.765e^{-8}$$

$$\text{and } t = T - 273.15$$

#### A3.3.1.1.8 Refractive index of air

The index of refraction of air ( $n$ ) depends on frequency ( $\nu$ ), pressure ( $P$ ), temperature ( $T$ ) and water vapor amount (partial pressure  $P_{H_2O}$ ). Since the original Edlén equation was published in the early 1960's [Edlén, 1966], many revised empirical formulas have been published based on the new measurements. We use a revision of Edlén by Birch and Downs [1993 and 1994]:

$$\begin{aligned} n &= n_{tp} - f \cdot (a_9 - a_{10} \nu^2) \cdot 10^{-10}; \\ n_{tp} - 1 &= \frac{P(n_s - 1)}{a_5} \cdot \frac{[1 + 10^{-8}(a_6 - a_7 t)P]}{(1 + a_8 t)}; \text{ and} \\ (n_s - 1) \cdot 10^{-8} &= a_0 + a_1 \cdot (a_2 - \nu^2)^{-1} + a_3 (a_4 - \nu^2)^{-1}; \end{aligned} \quad (A.41)$$

where  $a_0$  to  $a_{10}$  are constants ( $a_0 = 8342.54$ ;  $a_1 = 2406147.0$ ;  $a_2 = 130.0$ ;  $a_3 = 15998.0$ ;  $a_4 = 38.9$ ;  $a_5 = 96095.43$ ;  $a_6 = 0.601$ ;  $a_7 = 0.00972$ ;  $a_8 = 0.003661$ ;  $a_9 = 3.7345$ ;  $a_{10} = 0.0401$ ; ),  $\nu$  is frequency in  $\text{mm}^{-1}$ ,  $P$  is pressure in Pa,  $t$  is temperature in  $^{\circ}\text{C}$  ( $t = T - 273.15$ ), and  $f$  is the partial pressure of water vapor.

Although the above formula was derived from measurements of visible and near infrared region, other measurements suggest that it could be extrapolated to the infrared region [Coleman *et al.*, U.S. NBS, "Table of Wavenumbers", 1960]. Note that frequency ( $\nu$ ) only has a secondary effect on  $n$ , so that the ray-trace step simply uses the averaged frequency for the forward model spectrum range in the calculation.

### A3.3.1.7: Non-LTE

The single-line volumetric absorption  $\kappa_\nu$  and local thermal radiance  $R_\nu$  is given by

$$\kappa_\nu = \frac{h\nu}{4} \bar{B} (g_u n_\ell - g_\ell n_u) \phi_\nu \quad (\text{A.42})$$

and

$$R_\nu = \frac{h^2 \nu^4}{2\pi c^2} g_\ell n_u \chi_\nu, \quad (\text{A.43})$$

where

$$\chi_\nu = \phi_\nu e^{-h(\nu - \nu_o)/kT}, \quad (\text{A.44})$$

where  $n_\ell$  and  $n_u$  are the number density populations of the lower and upper V-R states and the constant integers  $g_\ell$  and  $g_u$ , are the respective single state degeneracy factors.

This result is a general one for a two-level system. The lineshapes,  $\chi_\nu$  and  $\phi_\nu$ , are functions of the bulk thermodynamic quantities such as pressure, temperature, plus individual gas densities which can separately influence the lineshapes. The populations are given by the Boltzman distribution only under conditions of local thermodynamic equilibrium. In the presence of a strong radiation field, or under conditions for which the relaxation rates are slow with respect to physical processes influencing the state populations, the upper and lower state populations are not simply related through Boltzmann factors associated with a characteristic temperature for the system and the source function for the radiance is no longer given by the Planck function.

In the present case for TES observations, several assumptions can be made which significantly simplify the Non-LTE problem: (1) the relevant transitions occur at low pressure so that the Doppler shape is dominant with the line shape for emission and absorption being the same; (2) the system is in translational equilibrium with a characteristic kinetic temperature (affects only the Doppler width); and (3) the system is in rotational equilibrium with a characteristic rotational temperature. In the present formulation, the Non-LTE radiative transfer is developed as an extension of the LTE radiative transfer minimizing complexity and computational cost. The Non-LTE vibrational state population variables can be used to relate the Non-LTE single-line absorption and radiance to the same quantities calculated for an atmosphere in equilibrium at the characteristic temperature  $\bar{T}$ . The relationship between non-equilibrium and equilibrium radiative properties for a single line can be summarized by

$$\kappa_\nu = \left[ \frac{g_u n_\ell - g_\ell n_u}{g_u n_\ell^e - g_\ell n_u^e} \right] \kappa_\nu^e \quad (\text{A.45})$$

and

$$R_v = \frac{n_u}{n_u^e} R_v^e, \quad (\text{A.46})$$

which can also be written in terms of the Planck function as

$$R_v = \frac{n_u}{n_u^e} B_v(\bar{T}) K_v^e. \quad (\text{A.47})$$

The superscript  $e$  denotes the equilibrium values of the respective quantities.

The ratios of non-LTE vibrational populations to their equilibrium values are given as enhancement (or depletion) ratios,

$$r_\ell = \frac{n_\ell}{n_\ell^e} \quad \text{and} \quad r_u = \frac{n_u}{n_u^e}. \quad (\text{A.48})$$

The single-line contributions to  $K_v$  and  $C_v$  due to a transition with wavenumber value  $\nu_o$  can be expressed simply in terms of these ratios according to

$$K_v = \left[ \frac{r_\ell - r_u \Delta}{1 - \Delta} \right] K_v^e \quad (\text{A.49})$$

and

$$C_v = \left[ \frac{r_\ell - r_u}{1 - \Delta} \right] K_v^e \quad (\text{A.50})$$

where  $\Delta$  is the Boltzman factor,

$$\Delta = \frac{g_\ell n_u^e}{g_u n_\ell^e} = e^{-h\nu_o/k\bar{T}}. \quad (\text{A.51})$$

The factors in brackets can be viewed as Non-LTE line strength correction factors. The functions,  $K_v$  and  $C_v$ , are obtained from the equilibrium values of the spectral absorption coefficients tabulated for individual vibrational states of a given molecular species. The quantities required for the calculation are  $r_\ell$ ,  $r_u$  and  $\nu_o$  for each Non-LTE vibrational state.

The complete solution of the radiative transfer equation for a homogeneous layer with column amount,  $u$ , is given by

$$L_v = L_v^o e^{-K_v u} + B_v(\bar{T}) \left[ 1 - \frac{C_v}{K_v} \right] [1 - e^{-K_v u}] \quad (\text{A.52})$$

where  $L_v^o$  is the radiation at the path boundary. The effect of solving the non-equilibrium problem for a homogeneous layer is effectively to modify the line strengths (equilibrium absorption coefficients) contributing to the local absorption coefficient  $K_v$ , and to replace the Planck function  $B_v$  by the high resolution function  $B_v(\bar{T})[1 - C_v / K_v]$ .

### A3.3.1.5.1:Non-LTE:NO Example

Non-LTE will occur under conditions for which relaxation rates are slow with respect to physical processes influencing the state populations. Initial testing and sensitivity studies using TES LBLRTM are performed using the method outline above in section A3.3.1.5. The Non-LTE vibrational temperatures for NO at  $v=1$  state were obtained from Funke and Puertas [2000] Non-LTE model (refer to Figure A-3 and Figure A-4), and the mixing ratio from the AFGL NO profile [Anderson, et. al, 1986] (refer to Figure A-5). The results from the Non-LTE model for NO( $v \leq 2, J, S$ ) in Figure A-3 show that there is significant departure from LTE for NO( $v \geq 1$ ) in the stratosphere daytime as low as 15 km due to the production by NO<sub>2</sub> photolysis. The issue of rotational and spin distributions of NO( $v=1,2$ ) shown to be in Non-LTE above ~110 km must also be evaluated.

Figure A-3: NO kinetic,  $v=1$ , and  $v=2$  vibrational temperatures in the daytime. Data provided by Funke and Puertas [2000].

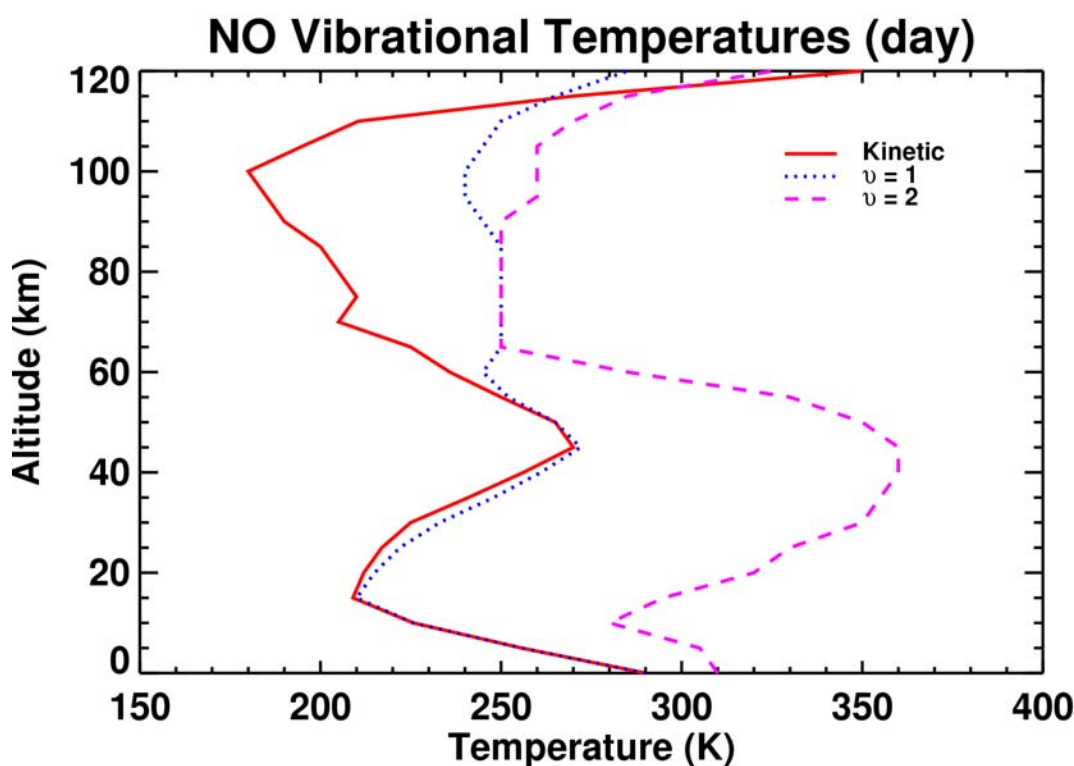


Figure A-4: NO kinetic,  $v=1$ , and  $v=2$  vibrational temperatures in the nighttime. Data provided by Funke and Puertas [2000].

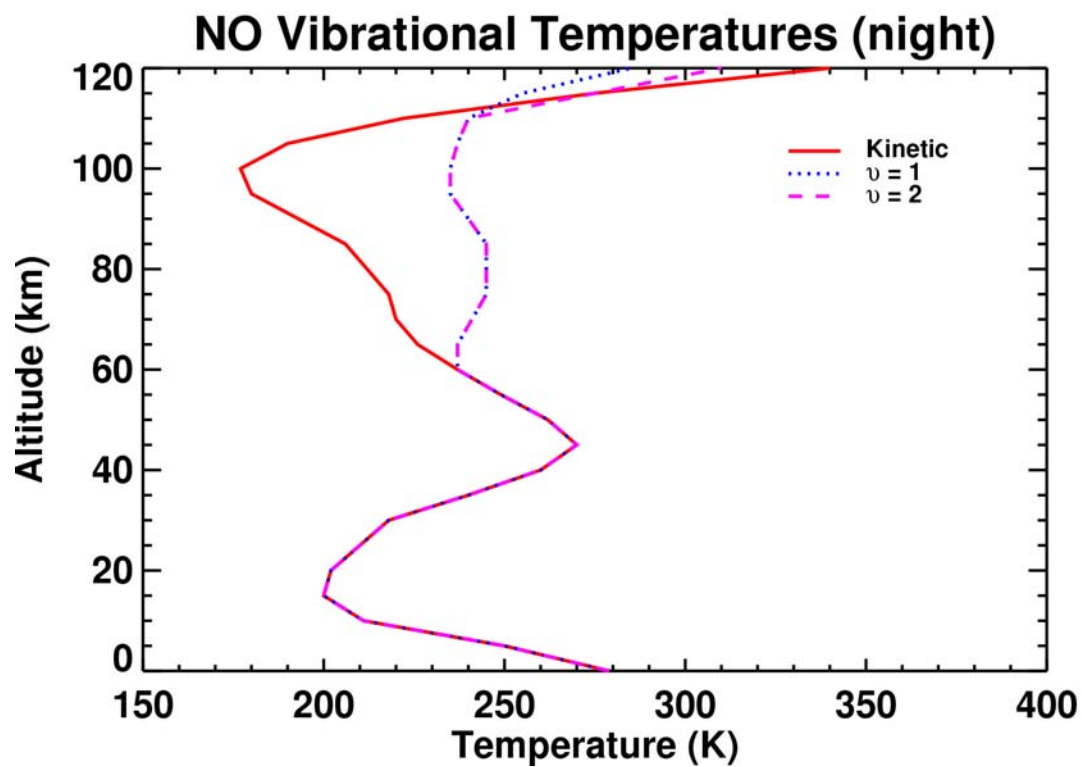
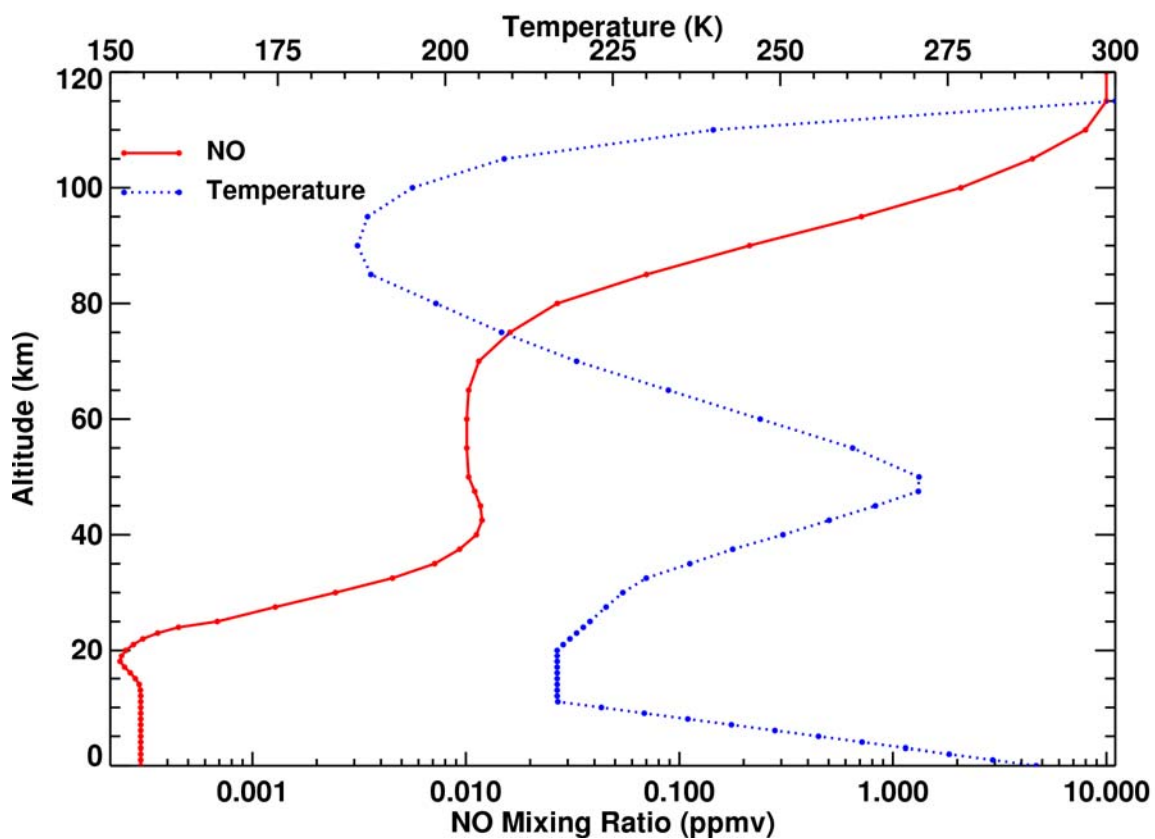
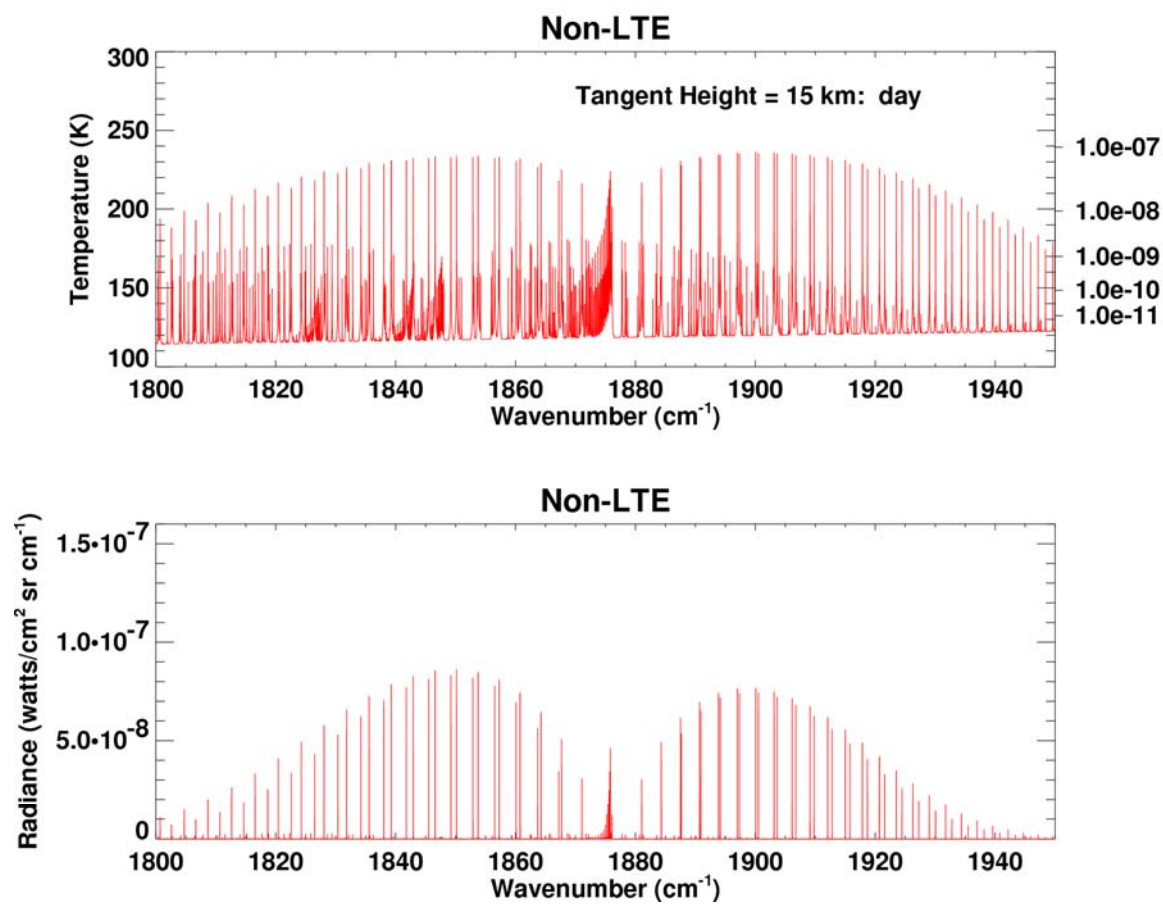


Figure A-5: US standard atmosphere profiles of NO mixing ratio and temperature [Anderson et. al., 1986].

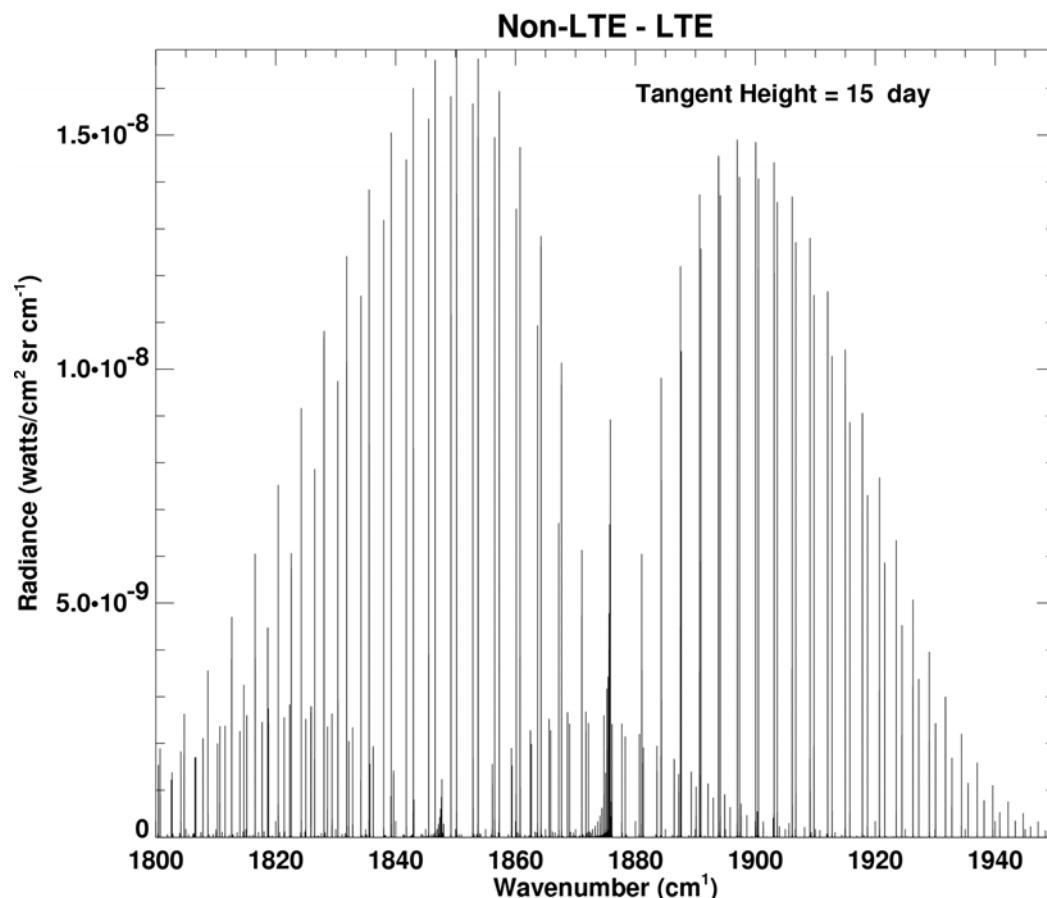


**Figure A-6: TES LBLRTM computed spectra of NO under Non-LTE ( $v=1$ ) daytime conditions for a limb path with a tangent height of 15 km. The results are plotted in both brightness temperature (top) and radiance (bottom).**





**Figure A-7: Difference plot between TES LBLRTM calculated radiances under Non-LTE ( $v=1$ ) and LTE (kinetic temperature) conditions.**



NO radiances have been computed under both LTE and Non-LTE( $v=1$ ) conditions for paths with tangent heights of 15 and 30 km during both day and night. Figure A-6 is the TES LBLRTM computed spectra of NO under Non-LTE daytime conditions for a tangent height of 15 km using inputs given in Figure A-3 and Figure A-5. The differences between the NO Non-LTE and LTE for this example are shown in Figure A-7 and have a maximum value of  $8.4 \times 10^{-8} \text{ W/cm}^2 \text{ sr cm}^{-1}$ . This difference corresponds to a percent maximum relative difference of  $\sim 20\%$ . These differences neglect the effect of thermospheric rotational/spin Non-LTE. Similar calculations were performed for a tangent height of 30 km under both day and night conditions and summarized in Table A-1. These differences in radiation due to Non-LTE effects in the stratosphere and thermosphere will have a significant impact on TES tropospheric NO retrievals and will be taken into consideration in the retrieval process as outlined in Section 3.3.1.5.

**Table A-1: Summary of results for Non-LTE vs. LTE TES LBLRTM calculations.**

Day/Night	Tangent Height (km)	Maximum Non-LTE NO Radiance ( $\text{W/cm}^2 \text{ sr cm}^{-1}$ )	Non-LTE - LTE Radiance ( $\text{W/cm}^2 \text{ sr cm}^{-1}$ )	Maximum Relative Difference (%)
DAY	30	$1.27 \times 10^{-7}$	$2.65 \times 10^{-8}$	21
DAY	15	$8.4 \times 10^{-8}$	$1.7 \times 10^{-8}$	20
NIGHT	30	$8.5 \times 10^{-8}$	$9.6 \times 10^{-10}$	1.1
NIGHT	15	$5.9 \times 10^{-8}$	$8.8 \times 10^{-10}$	1.5

### A3.3.2.1: Map of Earth Surface Composition

#### Global Land Cover Characteristics Data Base

This appendix describes an existing source of global land cover maps with 1 km resolution and a choice of land classification schemes. This database was generated by the U.S. Geological Survey (USGS) Earth Resources Observation System (EROS) Data Center, the University of Nebraska-Lincoln (UNL) and the Joint Research Centre of the European Commission and is described in more detail at: <http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html>. Their maps are derived primarily from 1 km resolution composites of normalized difference vegetation index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR) for the 12 month period of April 1992-March 1993. (NDVI values are the difference divided by the sum of the near infrared (channel 2) and visible (channel 1) reflectance values, after calibration and atmospheric corrections). The strategy for global land cover characterization is given in Loveland *et al* [1991, 1995] and Brown *et al* [1993] and an AVHRR data quality evaluation is described in Zhu and Yang [1996]. The global land cover maps are available in 6 different classifications schemes with a range of 10 to 94 land cover types. These schemes are optimized to provide relevant information for research in areas such as atmospheric general circulation models and land use studies. Three of these classification schemes include urban/built-up areas as a land cover type, a useful distinction for our purposes. These are the Global Ecosystems classification (94 classes), Olson [1994 a&b]; the USGS Land Use/Land Cover System (24 classes), Anderson *et al* [1976]; and the International Geosphere Biosphere Programme (IGBP) Land Cover Classification (17 classes), Belward [1996]. Although we should not preclude the use of the more detailed Global Ecosystems classification, the USGS Land Use/Land Cover system (listed below) has been chosen for the initial algorithm development. The IGBP scheme, although simpler, was not chosen because there were no classes to distinguish moist vs. dry vegetation, an important distinction because of significant spectral IR reflectance differences. None of the land cover classifications in this database distinguished ice from snow, and an additional database may be needed for these areas.

**Table A-2: USGS Land Use/Land Cover System Legend and Assignment of Material Type from the ASTER Spectral Library (<http://speclib.jpl.nasa.gov/>)**

Value	Code	Description	Default material types to use for surface emissivity
1	100	Urban and Built-Up Land	construction asphalt, grass, deciduous
2	211	Dryland Cropland and Pasture	dry grass
3	212	Irrigated Cropland and Pasture	Grass
4	213	Mixed Dryland/Irrigated Cropland and Pasture	grass, dry grass
5	280	Cropland/Grassland Mosaic	grass, dry grass
6	290	Cropland/Woodland Mosaic	grass, deciduous, conifer
7	311	Grassland	Grass
8	321	Shrubland	Deciduous
9	330	Mixed Shrubland/Grassland	Deciduous, grass
10	332	Savanna	dry grass
11	411	Deciduous Broadleaf Forest	Deciduous
12	412	Deciduous Needleleaf Forest	Conifer
13	421	Evergreen Broadleaf Forest	Conifer
14	422	Evergreen Needleleaf Forest	Conifer
15	430	Mixed Forest	Deciduous, conifer
16	500	Water Bodies	fresh or salt water
17	620	Herbaceous Wetland	Conifer
18	610	Wooded Wetland	Conifer
19	770	Barren or Sparsely Vegetated	brown gravelly sandy loam
20	820	Herbaceous Tundra	Deciduous
21	810	Wooded Tundra	Conifer
22	850	Mixed Tundra	Deciduous, conifer
23	830	Bare Ground Tundra	dry grass
24	900	Snow or Ice	coarse granular snow

### A3.3.3 Radiative Transfer for Clouds and Aerosols

#### A3.3.3 Radiative Transfer for Clouds and Aerosols

Aerosols and clouds (scattering materials) have the potential to impact TES measurements. This appendix will describe the overall strategy for dealing with scattering materials and refer the reader to the relevant sections in the ATBD.

The first step in dealing with scattering materials is to identify measurements that have been impacted. We will use the framework of sorting the data into cases of no clouds, broken or highly inhomogeneous clouds, optically thick clouds, and optically thin clouds. The basic strategy is to examine the brightness temperatures in the atmospheric window regions and use the values and variability of the values to classify the observations. This is discussed in detail in sections 3.5.5 and 3.5.6, pixel categorization.

Target scenes that are categorized as being free of clouds can be processed easily. If broken or highly inhomogeneous clouds are present, the target scene will be excluded from further processing. In the case of an optically thick cloud in the limb, detectors at and below the cloud will be excluded from further analysis. Light scattered into the field of view may need to be considered (see section 3.3.3.2). In nadir views, the cloud will be treated as the surface.

Cases with optically thin clouds in the nadir may be handled with gray body extinction cross sections. This is discussed in greater detail in section 3.3.3. Due to the horizontal inhomogeneity of clouds, attempting to include optically thick clouds in the limb is not recommended.

### A3.3.8.1: Line-by-Line Spectral Parameters

The line-by-line portion of the TES spectroscopic database contains transitions for individual infrared active molecular species and their isotopomers within the spectral range defined by the TES nadir and limb observations. The numbering of the species and format for the parameters are currently the same as in the HITRAN database. The HITRAN parameters are available through the internet or via an ftp site at the Smithsonian Astrophysical Observatory (<http://www.hitran.com>). The parameters and the contents of the HITRAN spectral parameters database were last reviewed for the 1996 HITRAN edition [Rothman et al., 1998]. Since that time, there have been significant improvements for some species. Here we describe the current status, updates, and known limitations of the current HITRAN parameters for the molecules and spectral regions of importance to TES. Laboratory work in progress, and published results not incorporated in HITRAN are also discussed. As was done for the ATMOS project [Brown et al., 1996], a TES spectroscopic database will be maintained to satisfy the specific needs of the TES project including all available sources (e.g. HITRAN, GEISA [Husson et al., 1999; 2000]). Status of current spectroscopy and anticipated needs proceeds on a molecule-by-molecule basis, with the description for each molecule in ascending wavenumber

#### *H<sub>2</sub>O (molecule 1)*

The significant deficiencies for water vapor on the HITRAN 1996 compilation in the thermal IR spectral region covered by TES have been greatly reduced as a result of the work of Toth (e.g. Toth [1998]). The major update includes the positions, intensities, air-broadening coefficients, self-broadening coefficients, and pressure-induced shifts and covers 500-2820 cm<sup>-1</sup>. Some transitions were found missing and were added from HITRAN 1996, so the update is not complete.

As was done for the ATMOS compilation [Brown et al., 1996], TES will treat HDO and a separate molecular species because of the large fractionation effects of HDO with respect to H<sub>2</sub>O [e.g., Moyer et al. 1996]. The current database does not include the updated positions and intensities of the HD<sup>16</sup>O  $\nu_2$  band derived by Flaud et al. [1986] and the more recent  $\nu_2$  HD<sup>16</sup>O,

HD<sup>17</sup>O, and HD<sup>18</sup>O position and intensity analysis results of Toth [1993]. The parameters of Flaud et al. [1986] have been regenerated (J.-M. Flaud, private communication) and are now available to the TES project with approximate air-broadened widths (C. P. Rinsland, private communication, 1998). Air-broadened pressure shifts are set to zero.

### *CO<sub>2</sub> (molecule 2)*

HITRAN infrared intensities require updating with a self-consistent calculation of energy levels including new measurements of positions, intensities, air-broadening width and air-broadened shift coefficients measured at Kitt Peak by the NASA Langley group in several spectral regions [Malathy Devi et al., 1998a,b,c] and new measurements in the 4500- to 8000 cm<sup>-1</sup> region by Miller [2001]. The 1996 HITRAN compilation parameters were based on a global least-squares fit of the energy levels of carbon dioxide [Rothman et al., 1998]. The new update should include the air-broadened pressure-shift coefficient measurements in the 10 μm laser bands, which have been demonstrated to be detectable in ground-based solar spectra [Malathy Devi et al., 1998c].

The update is of critical importance because of the use of CO<sub>2</sub> for temperature sounding by TES. Additional CO<sub>2</sub> measurements of intensities, broadening, and shift coefficients in the 4.2-4.5 μm region (<sup>12</sup>C<sup>16</sup>O<sub>2</sub>, <sup>13</sup>C<sup>16</sup>O<sub>2</sub>, and <sup>13</sup>C<sup>16</sup>O<sup>18</sup>O) and in the 10 μm laser bands are soon to be reported by the NASA Langley group (e.g. Malathy Devi et al. 2002]. The results were derived from room temperature 0.01-cm<sup>-1</sup> resolution laboratory spectra recorded at Kitt Peak. The spectroscopy of CO<sub>2</sub> in the infrared was reviewed by Malathy Devi et al. [1997].

### *O<sub>3</sub> (molecule 3)*

Simultaneous pure-rotation and 10-μm measurements of line intensities are needed to resolve the 3-4% discrepancy between measurements performed at Kitt Peak by the NASA Langley group [Smith et al., 2001] and values obtained at the Deutsches Zentrum für Luft und Raumfahrt (DLR) [Wagner et al., 2000] and at LPMA [Claveau et al., 2001]. The DLR and LPMA measurements are both lower than the Kitt Peak measurements, which are 1% higher than HITRAN 1996 [Rothman et al., 1998]. The Kitt Peak intensities agree with the current HITRAN values within experimental error. Field measurements indicate the current HITRAN values are accurate to better than 5% [Toon et al., 1999, plate 4]. If the 10-μm O<sub>3</sub> intensities are modified, the intensities in all other IR spectral regions must be scaled by the same factor to retain consistency. The DLR measurements from 16 spectra were at temperatures between 200 and 296 K and air pressures between 0.0 to 40 mbar were also analyzed to determine air-broadening coefficients, which were fitted with an empirical expansion in *m* and temperature [Wagner et al., 2000]. Those results differ significantly from values predicted by the current HITRAN compilation with important implications for the derivation of tropospheric ozone profiles from the TES nadir and limb-viewing spectra.

Updates of O<sub>3</sub> parameters on the 1996 HITRAN compilation have been summarized [Rinsland et al., 1998a]. Spectra of <sup>17</sup>O-enriched ozone samples recorded at 0.005-cm<sup>-1</sup> resolution were analyzed to derive the line positions and intensities for the *v*<sub>1</sub> and *v*<sub>3</sub> bands of <sup>16</sup>O<sup>17</sup>O<sup>16</sup>O [Heyart et al., 1992] and <sup>16</sup>O<sup>16</sup>O<sup>17</sup>O [Heyart et al., 1993]. As described by Rinsland et al. [1998a], these parameters, which were not included on HITRAN 1996 [Rothman et al., 1998] and are still not in that database. A combined list was used to identify isolated lines of the *v*<sub>3</sub> bands of <sup>16</sup>O<sup>17</sup>O<sup>16</sup>O and <sup>16</sup>O<sup>16</sup>O<sup>17</sup>O in both high resolution ground-based and balloon-borne stratospheric solar absorption

spectra. As shown in that work, they are detectable in atmospheric spectra, and hence should be added to the TES database.

Bands of  $O_3$  at 4.7  $\mu m$  are about one third as strong as those at 10  $\mu m$  and are important absorbers in the region that will be used to retrieve CO profiles from the TES spectra. The first high-resolution analysis of the  $v_1 + v_3$  bands of  $^{16}O^{16}O^{18}O$  and  $^{16}O^{18}O^{16}O$  at 4.8  $\mu m$  was performed by Flaud et al. [1994]. On the basis of that work, isolated lines of both heavy isotopic species were identified in high resolution ground-based solar absorption spectra by Arlander et al. [1994] and Goldman et al. [1998]. Line parameters for the  $v_1 + v_3$  bands of  $^{16}O^{18}O^{16}O$  and  $^{16}O^{16}O^{18}O$  [Flaud et al., 1994] and  $^{16}O^{17}O^{16}O$  and  $^{16}O^{16}O^{17}O$  [Perrin et al., 2001] should be added to the TES database. However, users must keep in mind that the corresponding intensities are not really accurate since they were calculated using the transition moments of the main isotopic species  $^{16}O_3$ .

Modeling of line mixing may be required for accurate simulations in Q-branch regions. As models suggest non-LTE may occur above 50 km, high vibrationally excited transitions should be added to the database, at least in the 10- $\mu m$  region.

#### *N<sub>2</sub>O (HITRAN molecule 4).*

Infrared measurements of positions, intensities, air-broadening coefficients and their temperature dependence, and pressure-shift coefficients obtained by Toth [2000] need to be made available to the public databases in HITRAN format. Additionally, an extensive set of line intensity measurements has been obtained from 4300-5200  $cm^{-1}$  [Daumont et al., 2001], and a linelist has been generated, though not in HITRAN format (J. Vander Auwera, private communication, 2001). There is good agreement with the results of Toth in regions of overlapping intensity data. Line intensities of  $^{14}N_2^{16}O$  measured in the 10- $\mu m$  region agree well with those on the HITRAN 1996 [Rothman et al., 1998] and GEISA 1997 [Jacquinet-Husson et al., 1999] line-parameter compilations, except for some disagreements for the 0001-1000 and 0220-0000 bands [Daumont et al., 2001].

#### *CO (HITRAN molecule 5)*

The new, self-consistent calculated set of ro-vibrational line intensities [Chackerian and Freedman, 2001] for the large range of vibrational quantum numbers need to replace current values in the public databases. This improvement is needed primarily for the intensities of the lines in the overtone bands.

#### *CH<sub>4</sub> (HITRAN molecule 6)*

HITRAN contains a total replacement of the linelist for this molecule as of February 2001 with a four-fold increase in the number of lines. However, at present there is no documentation of the changes.

#### *O<sub>2</sub> (HITRAN molecule 7)*

Spectroscopic parameters for both discrete electric quadrupole transitions and the pressure-induced (1-0) band exist on HITRAN 1996 [Rothman et al., 1998]. More precise measurements of the pressure-induced band (1-0) band have been reported recently by Lugez et al. [1998]. The

new results are in good agreement with the earlier less precise measurements of Orlando et al. [1991] on O<sub>2</sub> and O<sub>2</sub>/N<sub>2</sub> mixtures and Thibault et al. [1997] on pure O<sub>2</sub>.

#### *NO (HITRAN molecule 8)*

As noted by Rothman et al. [1998], the total internal partition functions for NO are incorrect in the HITRAN 1996 database due to an error in the nuclear spin statistical weight factors.

#### *NO<sub>2</sub> (HITRAN molecule 9)*

Progress in the analysis of NO<sub>2</sub> since the HITRAN 1996 database [Perrin et al., 1998] has been described by Perrin et al. [2000] with a focus on the 6.2  $\mu\text{m}$  region, which contains the strongest band in the infrared, the  $\nu_3$ . The updates in that region include new measurements of positions and intensities of isotopic and hot bands. The hot band measurements may be important for modeling of non-LTE effects in the TES spectra of the upper atmosphere.

Dana et al. [1997] have reported self-, N<sub>2</sub>-, and O<sub>2</sub>-broadening coefficients of NO<sub>2</sub> lines in the  $\nu_1 + \nu_3$  band at 3.4  $\mu\text{m}$ . The study found a slight rotational dependence of the broadening coefficients versus N", whereas no significant dependence was observed versus K<sub>a</sub>". An empirical relation was derived to compute air-broadening coefficients at 296 K with an uncertainty of about  $\pm 10\%$  for values of N" and K<sub>a</sub>" less than 40 and 10, respectively. The authors note that for typical lines used for atmospheric applications, the single value reported in earlier editions of the HITRAN database for all lines of all bands of NO<sub>2</sub> can differ by more than 20% from the measured values [Dana et al., 1997]. A preliminary analysis of unpublished spectra of the 1600  $\text{cm}^{-1}$  NO<sub>2</sub> band indicates that the widths of these lines are also too small in the previous HITRAN linelist with tests indicating that the changes produce a 10% increase in the retrieved mixing ratio of NO<sub>2</sub> at 25 km and little effect above 30 km [Sen et al., 1998]. The updated NO<sub>2</sub> parameters are available as a Sept. 2001 update from the HITRAN website.

#### *HNO<sub>3</sub> (HITRAN molecule 12)*

Unpublished fits to Mark IV stratospheric balloon spectra with molecular constants derived by Toth (presented as a poster at the 2001 spectroscopic line parameters workshop in San Diego, CA) show improved fits in the region of the overlapping  $\nu_5$ ,  $2\nu_9$  bands at 11  $\mu\text{m}$ . However, even if some progress were achieved recently (J.-M. Flaud, A. Perrin, and J. Orphal, private communication 2001), problems remain in simulating the narrow and very intense 885- $\text{cm}^{-1}$  hot band and other bands throughout the thermal IR. Retrievals from Mark IV balloon spectra indicate that the normalization of intensities in the HITRAN 2000/2001 database are inconsistent for the major bands at 5.7, 7.5, and 11  $\mu\text{m}$ . Accurate and consistent absolute intensity measurements are still needed for all observable bands throughout the IR.

Perrin et al. [1998] have reanalyzed the  $\nu_8 + \nu_9$  band at 1205  $\text{cm}^{-1}$  based on a 0.003- $\text{cm}^{-1}$  resolution laboratory spectrum recorded at the University of Denver. As in a recent analysis [Wang et al., 1997], the Hamiltonian for fitting the line positions takes into account the  $\Delta K \pm 2$  anharmonic resonance linking the rotational levels of the  $\nu_8=1$ ,  $\nu_9=1$  "bright" vibrational state with those of the  $\nu_7=1$ ,  $\nu_8=1$  "dark" vibrational state. However, in contrast to previous work,  $\nu_8 + \nu_9$  is noted to be a hybrid-type band with clearly identified B-type transitions among those of the strong A-type lines. The A- and B-type components of the transition moment operator of the  $\nu_8 + \nu_9$  band were

determined through a least-squares fit of experimental line intensities measured from the spectrum. The new analysis extends the assignments for the  $\nu_8 + \nu_9$  band to maximum rotational quantum numbers of  $J=74$  and  $K_a=49$  as compared to a maximum  $J$  value of 57 [Wang et al, 1997].

*OCS (HITRAN molecule 19).*

A recent study of high-resolution balloon-borne spectra [Goldman et al., 2000] showed that isotopic  $^{16}\text{O}^{12}\text{C}^{34}\text{S}$  lines are observable, and well as weak hot band transitions of  $\nu_3 + \nu_2 - \nu_2$  of  $^{16}\text{O}^{12}\text{C}^{32}\text{S}$ . The line positions and intensities for these bands have been already incorporated into the HITRAN database, but the air-broadening coefficients have not been updated to the level known about OCS.

*HOCl (HITRAN molecule 21).*

The absolute intensities of lines in the  $\nu_2$  band need to be updated based on simultaneous measurements in the infrared with a tunable diode laser and the far infrared by a Fourier transform spectrometer [Vander Auwera et al., 2000].

*HCN (HITRAN molecule 23).*

This molecule is now recognized as an important tracer of biomass burning with emissions that originate primarily in the smoldering phase of combustion [Rinsland et al. 1998b]. Positions and intensities on HITRAN were calculated more than 20 years ago. Air-broadening coefficients are taken as room-temperature  $\text{N}_2$ -broadening coefficients measured at  $0.06\text{-cm}^{-1}$  resolution over a decade ago [Smith et al., 1984]. A laboratory run at Kitt Peak in November 2001 has been completed to obtain HCN air-,  $\text{N}_2$ -, and  $\text{O}_2$ -broadening coefficients as a function of temperature for lines in the  $2_2$ ,  $2\nu_2$ , and  $\nu_1$  regions, which are observable with ground-based and space-borne instruments. Hot-band lines are missing in the  $\nu_1$  region on the 2001 HITRAN compilation.

*HCOOH (HITRAN molecule 25).*

Formic acid is ubiquitous in the troposphere and an important tracer of biomass burning emissions. Spectral parameters have been generated for the  $\nu_6$  region, which contains the strongest band located in an atmospheric window [Perrin et al., 1999]. This feature is suitable for quantitative analysis based on absorption by the  $\nu_6$  band Q branch at  $1104.7\text{ cm}^{-1}$  but the feature is overlapped by a temperature-sensitive line of HDO at  $1104.87594\text{ cm}^{-1}$ , which was missing in earlier versions of HITRAN, but is now included.

*$\text{C}_2\text{H}_6$  (HITRAN molecule 27).*

Recently, assignments, improved positions, intensities, and air-broadening coefficients and their temperature dependence have been derived for the strong and sharp  $^p\text{Q}_3$  subbranch of the  $\nu_7$  band at  $2976.8\text{ cm}^{-1}$  [Pine and Stone; 1996; Rinsland et al., 1998c; Pine and Rinsland, 1998]. This strong and sharp feature is prominent in ground-based solar spectra [Rinsland et al., 1987; Rinsland et al., 1998c] and nearly free of atmospheric interferences. The new results were obtained from analysis of Doppler-limited and sub-Doppler molecular beam laboratory spectra. It may be possible to measure this  $\text{C}_2\text{H}_6$  feature in the TES nadir view spectra. Also, it should be noted that the TIPS program provided on the 1996 HITRAN CD ROM does not compute the  $\text{C}_2\text{H}_6$  total internal partition function correctly.



*COF<sub>2</sub> (molecule 29)*

Line assignments in the  $\nu_1$  band at 1943 cm<sup>-1</sup> are incorrect (J.-M. Flaud, private communications, 2001) and have to be fixed.

*ClONO<sub>2</sub> (HITRAN molecule 35).*

Current HITRAN absorption cross sections for the region of the  $\nu_4$  band Q branch at 780.2 cm<sup>-1</sup> should be replaced by temperature- and pressure-dependent 0.0009-0.008 cm<sup>-1</sup> resolution laboratory spectra measured between 190 and 296 K and 0.3 to 1.0 mbar measured by Birk and Wagner [2000]. Nearly 30 of these laboratory spectra have been analyzed with the JPL GFIT algorithm to generate the set of ClONO<sub>2</sub> “pseudolines” by simultaneously fitting transmission spectra produced from the laboratory absorption coefficient. Retrievals with the Mark IV spectra indicate a more consistent estimation of the stratospheric chlorine budget than earlier sets of parameters (G. C. Toon, private communication, 2001). A spectroscopic analysis of these bands is in progress and, if successful and validated, should be used in the future [Flaud et al., 2001b]. Additional measurements of low temperature absorption cross-sections are needed for the strong 1700-cm<sup>-1</sup> band.

Additional species

*COCIF (no HITRAN molecule number).*

At present, no parameters exist on the HITRAN database for this molecule, which possibly could be detected in lower stratospheric tropical regions from measurements of its  $\nu_1$  band near 1800 cm<sup>-1</sup>.

*COCl<sub>2</sub> (no HITRAN molecule number).*

The  $\nu_5$  band in the 830- to 860-cm<sup>-1</sup> region was recently reported from balloon-borne solar occultation spectra. This identification and the occurrence of the strong  $\nu_1$  band centered at 1827 cm<sup>-1</sup> [Toon et al., 2001] and the availability of limited spectroscopic parameters in both regions indicate a need for further studies to improve quantitative analysis for both bands.

*CH<sub>3</sub>OH (no HITRAN molecule number).*

The 1033-cm<sup>-1</sup> CO-stretch  $\nu_8$  band of ethanol is a prominent feature in spectra of biomass burning plumes (e.g. Worden et al., [1997]). Spectral features of this band are likely to be an important interference in retrievals of O<sub>3</sub> from TES spectra recorded under such conditions. To our knowledge, no line-by-line parameters are available for this band, though progress is being made on the analysis of all the IR bands [Xu and Lees, 2000].

*IR Cross-Sections*

The HITRAN compilation includes infrared absorption cross sections for molecules that cannot be reliably modelled by line-by-line methods. They are C<sub>2</sub>F<sub>6</sub>, CCl<sub>4</sub>, CFC-11, CFC-113, CFC-114, CFC-115, CFC-12, CFC-13, CFC-14, ClONO<sub>2</sub>, HFC-123, HFC-124, HFC-141B, HFC-142B, HCFC-21, HCFC-22, HCFC-225, HFC-125, HFC-134, HFC-134a, HFC-143a, HFC-152a,

HFC-34, HNO<sub>4</sub>, N<sub>2</sub>O<sub>5</sub>, and SF<sub>6</sub>. Some species are included both as line-by-line and absorption cross section files on HITRAN, so care is required to avoid duplication.

### *Partition Functions*

It is important to note that the partition functions supplied by HITRAN have several significant deficiencies as discussed by Goldman *et al.* [1998].

#### **A3.3.8.2: Cross-Section P-T Interpolation Program XSFINT**

##### **1. P-T Point outside table of temperature-pressure values**

In this case the "distance" away from every point in the table is calculated and compared to find the closest point. The distance calculation is based on linear distance formulas where the pressure is divided by 10 to give similar units in temperature and pressure.

##### **2. P-T Point inside table of temperature-pressure values**

This program picks points based on temperature lines where all temperatures within 2 degrees are considered to be on the same temperature line. A temperature line could look like

Temperature	Pressure
216	50.6
214.1	70.8
215.8	100.0

A table of pressures on temperature lines is constructed from which to pick points. There are four basic cases in the interpolate point outside table of temperature values; four points around target; three points around target; two points around target. The new cross-section records interpolated from the above cases are all written to a new cross-section file. The user can also select the points and interpolation method by hand rather than letting the program select the points and interpolation method.

##### **Four points around target**

In this case 2 points on the temperature line before and after the target temperature are found where the points surround the target pressure.

216.6,70.5	217.1,90.2 (temp line after)
210.0,80.0 (target point)	
200.1,69.9	201.0,89.9 (temp line before)

The corner pressures must be within 10% of each other (216.6,70.5 with 200.1,69.9 & 217.1,90.2 with 201.0,89.9) or the tightest diagonal line is picked and the 2 point temperature interpolate is activated, otherwise the 4 point interpolate is activated.

**Three points around target**

In this case either the temperature line above or below the target contains only one point.

216.6,70.5	217.1,90.2 (temp line after)
	210.0,80.0 (target point)
200.1,69.9	(temp line before)

or

	216.6,70.5	217.1,90.2 (temp line after)
	210.0,80.0 (target point)	
	201.0,89.9	(temp line before)

If the target temperature is within 5 degrees of the temperature line with 2 points, then a 2 point pressure interpolate is activated between those two points. If the target temperature is not close enough to the temperature line with two points, then two points are chosen that create a diagonal (200.1,69.9 with 217.1,90.2 or 216.6,70.5 with 201.0,89.9) then the two point temperature interpolate is activated.

**Two points around target**

In this case one point on the temperature line before and after the target are used. If both points are either greater or smaller in pressure that the target, then the closest in pressure is used as the new point. If one of the two points are within 4% in temperature and 15% in pressure of the target, then that point is used as new point. If both points are within the 4% and 15% then the closest in temperature is used. If none of the above special cases occur then the 2 point temperature interpolate is activated.

**Two point Temperature Interpolate**

Two point temperature interpolate does a linear interpolate in temperature between the two pressure/temperature cross-section points for each point in the cross-sections.

**Two point Pressure Interpolate**

Two point pressure interpolate does a log interpolate in pressure between the two pressure/temperature cross-section points for each point in the cross-sections. (Note In the code the two point pressure interpolate is noted as a 3 point interpolate since two point temperature interpolate is noted as a 2 point interpolate)

**Four point Interpolate**

Four point interpolate does a linear interpolate in temperature between the side pressure/temperature cross-section points, then a log interpolate in pressure between the two new temperature points resulting from the linear temperature interpolate.

## **XSFINT Source Code**

Xsfint has been compiled and tested on roma in /home/goldman/xsctions/interp. The source code for xsfint is all in one FORTRAN90 file called xsfint.F90. It contains two modules and one main code. The main code is at the end of the file, and must be there for it to use the two modules.

The program has code to create plots using NCAR GKS graphics. The graphics code is currently disabled using conditional compilation with #define, #ifdef, #endif. All sections of graphics code are bracketed in #ifdef NCARGKSOUTPUT, #endif NCARGKSOUTPUT. The first line in the source code has a comment line

```
!#define NCARGKSOUTPUT
```

Uncommenting this line, (removing the "!"), activates the graphics code. The source file is named with .F90 instead of .f90 to activate the pre-processor that processes the NCARGKSOUTPUT lines. To compile xsfint, activate f90 as follows

```
f90 -o xsfint xsfint.F90
```

## **XSFINT Input**

The input file format is as follows

line1 -input cross-section filename

line 2 -output cross-section filename

line 3 -target temperature target pressure interpolate select

interpolate select

0 = Automatic pick of points to interpolate and interpolate method

1 = Use the temperature, pressure shown on line 4 to select a record from the cross-section file as the new point. (manual pick nearest point)

2 = Use the temperature, pressure shown on line 4 and 5 to select 2 records from the cross-section file to do a two point temperature interpolate on.

3 = Use the temperature, pressure shown on line 4 and 5 to select 2 records from the cross-section file to do a two point pressure interpolate on.

4 = Use the temperature, pressure shown on line 4, 5, 6 and 7 to select 4 records from the cross-section file to do a four point interpolate on.

Lines to specify manual selections contain

temperature pressure

There can be multiple target points selected in a run, each possibly with different interpolation selectors.

There is an example case on roma in /home/goldman/xsctions/interp and is named cfc22.test.input. It contains

../cfc22.xsect (cross-section file to read)

cfc22.test.output (cross-section file to create)

220.0 50.0 3 (target 220.0,50.0 manual select points)

216.0 176.8 (point 1 for 2 point pressure interp)

216.0 40.9 (point 2 for 2 point pressure interp)

240.0 300.0 0 (target 240.,300. auto select points & interp)

226.0 223.0 2 (target 226.0, 223.0 manual select points)

237.0 270.4 (point 1 for 2 point temperature interp)

216.0 176.8 (point 2 for 2 point temperature interp)

### **Running XSFINT**

To run xsfint on the test case on roma type

xsfint <cfc22.test.input >& cfc22.test.output

This reads cfc22.test.input and creates cfc22.new.xsect and cfc22.test.output.

### **List of files**

All files are on ms are in /GOLDMAN/VARANAS/XSEC.JUNE.97 except where noted otherwise.

#### **CCL4**

Xsection file - ccl4.tar

Resolution - 0.03 cm<sup>-1</sup>

Fixed 0.0025 cm<sup>-1</sup> Spc file -ccl4.xsect.25

Avg Spc file - ccl4.xsect.avgspc

Table - table.ME0216 in goldman output subdirectory

Number of Files 32

Wavenumber range 750.0100-811.9900 cm<sup>-1</sup>

#### **CFC11**

Xsection file - cfc11.tar

Resolution - 0.01, 0.03 cm<sup>-1</sup>

Fixed 0.0025 cm<sup>-1</sup> Spc file -cfc11.xsect.A.25  
cfc11.xsect.B.25

Avg Spc file - cfc11.xsect.avgspc.A  
cfc11.xsect.avgspc.B

Table - table.ME0131 (part a) in goldman output subdirectory  
table.ME7904 (part b) in goldman output subdirectory

Number of Files 55

Wavenumber range 810.0060-879.9930 cm<sup>-1</sup>  
1050.0000-1119.9930 cm<sup>-1</sup>

#### **CFC12**

Xsection file - cfc12.tar

Resolution - 0.01, 0.02, 0.03 cm<sup>-1</sup>

Fixed 0.0025 cm<sup>-1</sup> Spc file -cfc12.xsect.A.25  
cfc12.xsect.B.25

Avg Spc file - cfc12.xsect.avgspc.A  
cfc12.xsect.avgspc.B

Table - table.ME8745 (part a) in goldman output subdirectory  
table.ME6165 (part b) in goldman output subdirectory

Number of Files 51

Wavenumber range 850.0050-949.9950  $\text{cm}^{-1}$   
1050.0060-1199.9850  $\text{cm}^{-1}$

#### CFC22

Xsection file - cfc22.tar  
Resolution - 0.03  $\text{cm}^{-1}$   
Fixed 0.0025  $\text{cm}^{-1}$  Spc file -cfc22.xsect.25  
Avg Spc file - cfc22.xsect.avgspc  
Table - table.ME0088 in goldman output subdirectory  
Number of Files 7  
Wavenumber range 760.0300-860.000  $\text{cm}^{-1}$

#### SF6

Xsection file - sf6.tar  
Resolution - 0.03  $\text{cm}^{-1}$   
Fixed 0.0025  $\text{cm}^{-1}$  Spc file -sf6.xsect.25  
Avg Spc file - sf6.xsect.avgspc  
Table - table.ME0112 in goldman output subdirectory  
Number of Files 7  
Wavenumber range 925.0100-955.000  $\text{cm}^{-1}$

#### CF4

Xsection file - cfc14.tar  
Resolution - 0.01, 0.03  $\text{cm}^{-1}$   
Fixed 0.0025  $\text{cm}^{-1}$  Spc file -cfc14.xsect  
Avg Spc file - cfc14.xsect.avgspc  
Table - table.ME0132 in goldman output subdirectory  
Number of Files 54  
Wavenumber range 1250.0050-1289.9975  $\text{cm}^{-1}$

### A3.4: Analytic Jacobians

The radiance at the satellite in terms of component contributions from the atmosphere and the surface, but neglecting the solar contribution may be written as

$$L_{sat} = L_L^\uparrow + \left( \epsilon B(T_{sfc}) + \alpha L_0^\downarrow \right) \mathcal{T}_{0,L} \quad (\text{A.53})$$

where  $L_L^\uparrow$  is the upwelling radiance contribution of the atmosphere from the surface to the level at the top of the atmosphere (TOA),  $\mathcal{T}_{0,L}$  is the transmittance of the atmosphere and  $L_0^\downarrow$  is the downwelling radiance at the surface. For a specularly reflecting surface,  $L_0^\downarrow$  is calculated for the same zenith angle as  $L_L^\uparrow$  and  $\alpha$  is the appropriate bi-directional reflectance. For a Lambertian surface,  $L_0^\downarrow$  is calculated at the diffusivity angle, the downwelling radiation scattered by the surface is taken to be isotropic and  $\alpha$  is the albedo.

Due to the form of the radiative transfer equation (equation 3.8), the analytic derivative of the radiance at the satellite with a change in parameter  $x_l$  at level  $l$ , is most expeditiously obtained in terms of associated layer quantities, so that we have

$$\frac{\partial L_{sat}}{\partial x_l} = \sum_j \frac{\partial L_{sat}}{\partial \bar{x}_j} \frac{\partial \bar{x}_j}{\partial x_l} \quad (\text{A.54})$$

in which  $x_l$  is an element of the retrieval vector associated with level  $l$  and  $\bar{x}_j$  is the associated layer quantity for layer  $j$ . Note that in general,  $x$  may be mixing ratio (log mixing ratio) or temperature in this context.

For the layer quantities, it is useful to separate the jacobian calculation into partial derivatives with respect to layer total optical depth ( $\tau_l$ ) and Planck function ( $B_l$ ) via the chain rule. Differentiating Equation (A.54), we obtain

$$\frac{\partial L_{sat}}{\partial x_l} = \frac{\partial L_{sat}}{\partial \tau_l} \frac{\partial \tau_l}{\partial x_l} \quad (\text{A.55})$$

for gas species, and

$$\frac{\partial L_{sat}}{\partial T_l} = \frac{\partial L_{sat}}{\partial \tau_l} \frac{\partial \tau_l}{\partial T_l} + \frac{\partial L_{sat}}{\partial B_l} \frac{\partial B_l}{\partial T_l} \quad (\text{A.56})$$

for layer temperature  $\bar{T}_l$ .

The next 5 sections of this appendix give (abbreviated) derivations for each of the terms in equations (A.55) and (A.56). This is followed by section A3.4.6, which gives the layer-to-level partials used in equation (A.54), section A3.4.7 where analytic pointing jacobians are derived and finally section A3.4.8 with results of analytic jacobian validation using finite difference jacobian calculations.

### A3.4.1 Partial with respect to layer optical depth (OD) $\frac{\partial L_{sat}}{\partial \tau_l}$

Differentiating (A.53), we obtain

$$\frac{\partial L_{sat}}{\partial \tau_l} = \frac{\partial L_L^\uparrow}{\partial \tau_l} + \alpha \frac{\partial L_0^\downarrow}{\partial \tau_l} \tau_{0,L} + \left( \varepsilon B(T_{sfc}) + \alpha L_0^\downarrow \right) \frac{\partial \tau_{0,L}}{\partial \tau_l} \quad (A.57)$$

Since

$$\tau_{0,L} = \prod_{k=0}^L e^{-\tau_k}, \quad \frac{\partial \tau_{0,L}}{\partial \tau_l} = -e^{-\tau_l} \prod_{k \neq l} e^{-\tau_k} \Rightarrow \frac{\partial \tau_{0,L}}{\partial \tau_l} = -\tau_{0,L} \quad (A.58)$$

equation (A.57) becomes

$$\frac{\partial L_{sat}}{\partial \tau_l} = \frac{\partial L_L^\uparrow}{\partial \tau_l} + \left[ \alpha \frac{\partial L_0^\downarrow}{\partial \tau_l} - \left( \varepsilon B(T_{sfc}) + \alpha L_0^\downarrow \right) \right] \tau_{0,L} \quad (A.59)$$

where  $\varepsilon=0$  and  $\alpha=1$  for limb calculations. We now need to evaluate the separate upwelling and downwelling terms.

#### A3.4.1.1 Downwelling OD partials $\frac{\partial L_0^\downarrow}{\partial \tau_l}$

For any layer  $l$ , the downwelling radiance at the corresponding level  $l$  is given by

$$L_l^\downarrow = L_{l+1}^\downarrow \tau_l + B(\overline{T_l})(1 - \tau_l) \quad (A.60)$$

Where  $L_{l=L}^\downarrow$  is initialized to zero radiance for the top of the atmosphere. Differentiating equation (A.60) we have

$$\frac{\partial L_l^\downarrow}{\partial \tau_l} = \left( B(\overline{T_l}) - L_{l+1}^\downarrow \right) \tau_l \quad (A.61)$$

At any stage in the recursive calculation, we can write the downwelling radiance at level 0,  $L_0^\downarrow$ , as the sum of two terms:

$$L_0^\downarrow = L_l^\downarrow \tau_{l,0} + L_{l,0}^\downarrow \quad (A.62)$$

*i.e.*, the downwelling radiance down to level  $l$  attenuated by the transmission from level  $l$  to level 0 plus the radiance contribution between levels  $l$  and 0, (see Figure A-8). Thus

$$\frac{\partial L_0^\downarrow}{\partial \tau_l} = \left( B(\overline{T_l}) - L_{l+1}^\downarrow \right) \tau_{l+1,0} \quad (A.63)$$

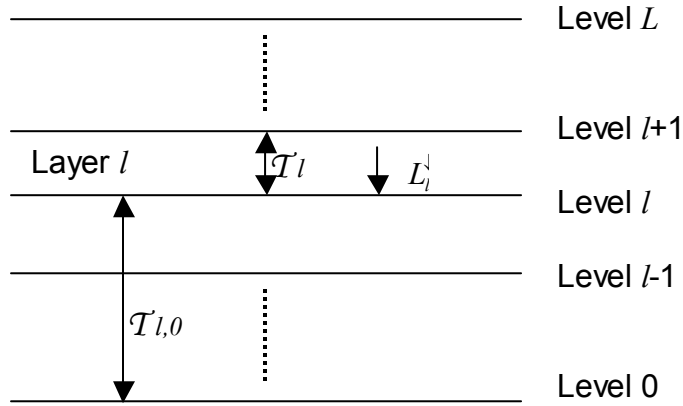


### A3.4.1.2 Upwelling OD partials $\frac{\partial L_L^\uparrow}{\partial \tau_l}$

We can write the upwelling radiance in terms of layer  $l$  as

$$L_L^\uparrow = \left[ L_l^\uparrow \tau_l + B_{eff}(\overline{T}_l, T_{l+1}, \tau_l)(1 - \tau_l) \right] \tau_{l+1,L} + L_{l+1,L}^\uparrow \quad (\text{A.64})$$

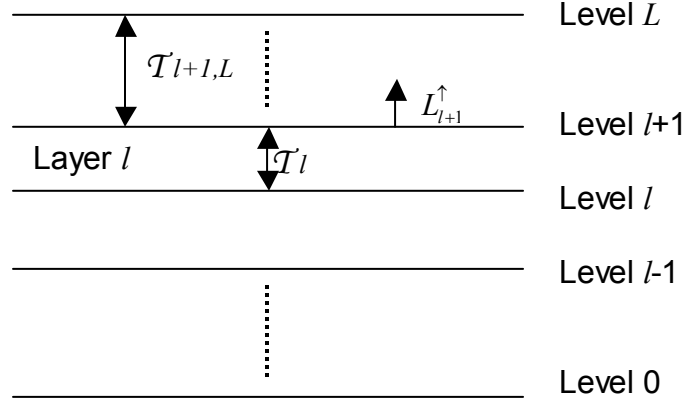
**Figure A-8: Layer and level view for downwelling OD jacobian calculation**



When  $L_{l=0}^\uparrow$  is initialized to the surface term:  $L_0^\uparrow = \varepsilon B(T_{sfc}) + \alpha L_0^\downarrow$  for nadir and to the “backside” or downwelling term:  $L_0^\uparrow = L_0^\downarrow$  for limb, equation (A.64) becomes the total radiance at the satellite,  $L_{sat}$ , as given in equation (A.53). For the upwelling radiative transfer, we apply the linear-in-tau approximation described in section 3.3.1.4. Differentiating equation (A.64) gives

$$\frac{\partial L_L^\uparrow}{\partial \tau_l} = \left( B_{eff}(\overline{T}_l, T_{l+1}, \tau_l) - L_l^\uparrow \right) \tau_{l+1,L} + \frac{\partial B_{eff}}{\partial \tau_l} (1 - \tau_l) \tau_{l+1,L} \quad (\text{A.65})$$

Figure A-9: Layer and level view for upwelling OD jacobian calculation



Since  $B_{eff}(\bar{T}_l, T_{l+1}, \tau_l) = B(\bar{T}_l) + \beta(\bar{T}_l, T_{l+1})F(\tau_l)$  where  $\beta(\bar{T}_l, T_{l+1}) = B(T_{l+1}) - B(\bar{T}_l)$  and  $F(\tau_l) = 1 - 2\left[\frac{1}{\tau_l} + \frac{T_l}{1 - T_l}\right]$ ; (with  $F(\tau_l) = \frac{\tau_l}{6}$  for small values of  $\tau_l$ ), we have

$$\frac{\partial B_{eff}}{\partial \tau_l} = \beta \frac{\partial F}{\partial \tau_l} \quad (\text{A.66})$$

where  $\frac{\partial F}{\partial \tau_l} = \frac{2}{\tau_l^2} - \frac{2T_l}{(1 - T_l)^2}$ ; (with  $\frac{\partial F}{\partial \tau_l} = \frac{1}{6}$  for small  $\tau_l$ ) is pre-computed and tabulated in the same way as  $F(\tau_l)$ .

Combining the downwelling and upwelling terms, equation (A.59) becomes:

$$\frac{\partial L_{sat}}{\partial \tau_l} = (B_{eff}(\bar{T}_l, T_{l+1}, \tau_l) - L_l^{\uparrow})T_{l,L} + \beta(\bar{T}_l, T_{l+1})\frac{\partial F}{\partial \tau_l}(1 - T_l)T_{l+1,L} + \alpha(B(\bar{T}_l) - L_{l+1}^{\downarrow})T_{l+1,0}T_{0,L} \quad (\text{A.67})$$

Note that the term  $-(\epsilon B(T_{sf}) + \alpha L_0^{\downarrow})T_{0,L}$  in equation (A.59) is accounted for since the upwelling radiance is initialized with  $L_{l=0}^{\uparrow} = \epsilon B(T_{sf}) + \alpha L_0^{\downarrow}$ , for nadir, ( $\epsilon=0$ ,  $\alpha=1$  for limb).

### A3.4.2 Partial of optical depth with respect to gas species VMR $\frac{\partial \tau_l}{\partial x_l}$

The layer optical depth is given by

$$\tau_l = \sum_m u_{l,m} \kappa_{l,m} = u_l \sum_m \kappa_{l,m} \bar{q}_{l,m} = u_l \kappa_l \quad (\text{A.68})$$

where  $u_{l,m}$  is the integrated path amount in layer  $l$  for species  $m$ ,  $\kappa_{l,m}$  is the absorption coefficient and  $\bar{q}_{l,m} = u_{l,m} / u_l$  is the layer average volume mixing ratio (VMR). For  $m \neq 1$ , *i.e.*, all species except H<sub>2</sub>O,

$$\frac{\partial \tau_l}{\partial q_{l,m}} = u_l \kappa_{l,m} \quad \text{or} \quad \frac{\partial \tau_l}{\partial \ln q_{l,m}} = \bar{q}_{l,m} u_l \kappa_{l,m} = \tau_{l,m} \quad (\text{A.69})$$

We then have the simple result that the optical depth (OD) partial with respect to log VMR is simply the species optical depth.

#### A3.4.2.1 Partial of optical depth with respect to H<sub>2</sub>O VMR $\frac{\partial \tau_l}{\partial q_{l,m=1}}$

For H<sub>2</sub>O ( $m=1$ ), we cannot neglect the dependence of H<sub>2</sub>O VMR on self-broadening for

absorption coefficients  $\left( \frac{\partial \kappa_{l,1}}{\partial q_{l,1}} \right)$  or the integrated path amount  $\left( \frac{\partial u_l}{\partial q_{l,1}} \right)$  and we must

separate the absorption ( $\kappa_{l,1}$ ) into both line ( $\kappa_{l,1}^{line}$ ) and continuum ( $\kappa_{l,1}^{cont}$ ) contributions. Including all these terms, we have

$$\frac{\partial \tau_l}{\partial \ln q_{l,1}} = \tau_{l,1} + \tau_{l,1}^{line} \frac{\partial \ln \kappa_{l,1}^{line}}{\partial \ln q_{l,1}} + \tau_{l,1}^{cont} \frac{\partial \ln \kappa_{l,1}^{cont}}{\partial \ln q_{l,1}} + \tau_l \frac{\partial \ln u_l}{\partial \ln q_{l,1}} \quad (\text{A.70})$$

Thus H<sub>2</sub>O VMR jacobians have three additional terms that are computed, compared to the other gas species VMR jacobians. These terms are described in the following sub-sections.

##### A3.4.2.1.1 H<sub>2</sub>O line self-broadening dependence $\tau_{l,1}^{line} \frac{\partial \ln \kappa_{l,1}^{line}}{\partial \ln q_{l,1}}$

We account for the self-broadening of H<sub>2</sub>O absorption lines by tabulating two sets of absorption coefficients,  $\kappa^{wet}$  and  $\kappa^{dry}$ , for pressures > 100 mb. Line absorption for H<sub>2</sub>O is then given by

$$\kappa_{l,1}^{line} = \kappa_l^{dry} + \left( \frac{\kappa_l^{wet} - \kappa_l^{dry}}{q_l^{wet} - q_l^{dry}} \right) (\bar{q}_{l,1} - q_l^{dry}) \quad (\text{A.71})$$

where  $q_l^{wet}$  is 90% of saturation vmr for the layer and  $q^{dry}$  is 1.0e-08 (layer independent). We then have

$$\tau_{l,1}^{line} \frac{\partial \ln \kappa_{l,1}^{line}}{\partial \ln \bar{q}_{l,1}} = \bar{q}_{l,1} u_{l,1} \left( \frac{\kappa_l^{wet} - \kappa_l^{dry}}{q_l^{wet} - q^{dry}} \right) \quad (A.72)$$

A3.4.2.1.2 H<sub>2</sub>O continuum dependence  $\tau_{l,1}^{cont} \frac{\partial \ln \kappa_{l,1}^{cont}}{\partial \ln \bar{q}_{l,1}}$

From equation 3.27, the absorption coefficient for water vapor continuum is given by:

$$\kappa_{l,1}^{cont} = \nu \tanh \left( \frac{h\nu}{2k_B \bar{T}_l} \right) \left[ \frac{\bar{P}_l \bar{T}_o}{\bar{P}_o \bar{T}_l} \right] \left( \bar{q}_{l,1} C_s (\bar{T}_l) + (1 - \bar{q}_{l,1}) C_f \right) \quad (A.73)$$

where  $C_s$  and  $C_f$  are the self and foreign broadened coefficients, respectively. We then have:

$$\tau_{l,1}^{cont} \frac{\partial \ln \kappa_{l,1}^{cont}}{\partial \ln \bar{q}_{l,1}} = u_{l,1} \kappa_{l,1}^{cont} \left( \frac{\bar{q}_{l,1} (C_s - C_f)}{\bar{q}_{l,1} C_s + (1 - \bar{q}_{l,1}) C_f} \right) \quad (A.74)$$

A3.4.2.1.3 Layer integrated path amount dependence on H<sub>2</sub>O VMR  $\tau_l \frac{\partial \ln u_l}{\partial \ln \bar{q}_{l,1}}$

Because water vapor at altitudes below 100mb is abundant enough to affect the integrated path amount through those layers, we account for this dependence in the H<sub>2</sub>O VMR jacobians. For nadir and most limb layers (all but the tangent and next to tangent layers), we can assume a straight path through the layer, *i.e.*, refraction can be neglected over the layer height. In these cases, we can write

$$g(M_{dry} u_l + M_{H_2O} \bar{q}_{l,1} u_l) = c \Delta p = \text{constant} \quad (A.75)$$

since we have a fixed pressure grid with  $\Delta p$  and we can assume gravitational acceleration,  $g$ , is constant over the layer.  $M_{dry}$  and  $M_{H_2O}$  are the molecular weights of dry air and water respectively. The constant  $c$  is the geometric correction for any straight path with respect to vertical ( $c=1$  for a vertical path). Differentiating this expression gives

$$\frac{\partial \ln u_l}{\partial \ln \bar{q}_{l,1}} = \frac{-1}{1 + \left( \frac{M_{dry}}{\bar{q}_{l,1} M_{H_2O}} \right)} \quad (A.76)$$

where  $\frac{M_{dry}}{M_{H_2O}} = \frac{28.96}{18} = 1.609$ . In general, the contribution from this term is small

(<1%) compared to the other corrections for H<sub>2</sub>O VMR jacobians.

The values of equation (A.76) have been compared to finite difference calculations with the ray-tracing code. For nadir and non-tangent layers for limb, the differences between this expression and the finite difference calculations are at most 3%. For limb tangent layers, the differences are around 30%. However, the effects of this correction are further reduced since it is subsequently multiplied by total transmission, which will be small in the limb case for layers near the surface where this correction is largest, due to water vapor continuum. Since we do not detect significant differences in the overall comparison of analytic to finite difference for limb H<sub>2</sub>O VMR jacobians due to the presence or absence of this term, we are not planning to modify the calculation in the limb tangent layers at this time.

### A3.4.3 Partial with respect to layer Planck (or effective Planck)

**function**  $\frac{\partial L_{sat}}{\partial B_l}$

Differentiating (A.53), we obtain

$$\frac{\partial L_{sat}}{\partial B_l} = \frac{\partial L_L^\uparrow}{\partial B_l} + \alpha \frac{\partial L_0^\downarrow}{\partial B_l} \tau_{0,L} \quad (\text{A.77})$$

#### Downwelling term

Following equation (A.62),  $L_0^\downarrow = [L_{l+1}^\downarrow \tau_l + B_l (1 - \tau_l)] \tau_{l,0} + L_{l,0}^\downarrow$  and

$$\frac{\partial L_0^\downarrow}{\partial B_l} = (1 - \tau_l) \tau_{l,0} \quad (\text{A.78})$$

#### Upwelling term

From equation (A.64),  $L_L^\uparrow = [L_l^\uparrow \tau_l + B_l^{eff} (1 - \tau_l)] \tau_{l+1,L} + L_{l+1,L}^\uparrow$  and

$$\frac{\partial L_L^\uparrow}{\partial B_l^{eff}} = (1 - \tau_l) \tau_{l+1,L} \quad (\text{A.79})$$

where  $B_l^{eff}$  is the layer effective Planck function for upwelling radiance calculations, assuming the linear-in-tau approximation, as discussed in section 3.3.1.4.

### A3.4.4 Partial of layer Planck (or effective Planck) function with

**respect to temperature**  $\frac{\partial B_l}{\partial T_l}$

The Planck function (in W/m<sup>2</sup>/sr/cm<sup>-1</sup>) is given by  $B_l = \frac{2hc^2\nu^3}{\exp\left(\frac{h\nu}{k_B \bar{T}_l}\right) - 1}$  with partial:

$$\frac{\partial B_l}{\partial \bar{T}_l} = \frac{B_l^2 \exp\left(\frac{h\nu}{k_B \bar{T}_l}\right)}{2c\nu^2 k_B \bar{T}_l^2} \quad (\text{A.80})$$

For the effective Planck function  $B_l^{eff} = B_l + \beta(\bar{T}_l, T_{l+1})F(\tau_l)$  with  $\beta = B(T_{l+1}) - B(\bar{T})$ , (see equation (A.66) for  $F(\tau_l)$ ), we have

$$\frac{\partial B_l^{eff}}{\partial \bar{T}_l} = \frac{\partial B_l}{\partial \bar{T}_l} + F(\tau_l) \left[ \frac{\partial B}{\partial T_{l+1}} \frac{\partial T_{l+1}}{\partial \bar{T}_l} - \frac{\partial B_l}{\partial \bar{T}_l} \right] \quad (\text{A.81})$$

where  $\frac{\partial T_{l+1}}{\partial \bar{T}_l}$  is the inverse layer-to-level partial for temperature given in section A3.4.6, with  $T_{l+1} = T_U$ , i.e., the temperature at the upper level of layer  $l$ .

### A3.4.5 Partial of optical depth with respect to temperature $\frac{\partial \tau_l}{\partial \bar{T}_l}$

Accounting directly for both line and continuum absorption, equation (A.68) becomes

$$\tau_l = \sum_m u_{l,m} (\kappa_{l,m}^{line} + \kappa_{l,m}^{cont}) \quad (\text{A.82})$$

with

$$\frac{\partial \tau_l}{\partial \bar{T}_l} = \sum_m u_{l,m} \left( \frac{\partial \kappa_{l,m}^{line}}{\partial \bar{T}_l} + \frac{\partial \kappa_{l,m}^{cont}}{\partial \bar{T}_l} \right) + \kappa_{l,m} \frac{\partial u_{l,m}}{\partial \bar{T}_l} \quad (\text{A.83})$$

Note that we are neglecting the dependence of the integrated path amounts in layers  $k$  where  $k > l$  on  $\bar{T}_l$ , which is small, but may need further study.

#### A3.4.5.1 Partial of line absorption with respect to temperature $\frac{\partial \kappa_{l,m}^{line}}{\partial \bar{T}_l}$

Line absorption coefficients are determined by a 3-point Lagrange interpolation in temperature, with  $\kappa_{l,m}^{line} = \sum_{i=0}^2 c_i(\bar{T}_l) \kappa_{i,(l,m)}$  where  $\kappa_{i,(l,m)}$  is the absorption coefficient tabulated at temperature  $T_i$ , in layer  $l$  for species  $m$ . Lagrange interpolation gives

$$c_i(x) = \frac{(x - x_0) \dots (x - x_{i-1})(x - x_{i+1}) \dots (x - x_n)}{(x_i - x_0) \dots (x_i - x_{i-1})(x_i - x_{i+1}) \dots (x_i - x_n)} \text{ and for 3-point interpolation, we have}$$

$$c_0(\bar{T}_l) = \left[ (T_1 - T_2) \bar{T}_l^2 + (T_2^2 - T_1^2) \bar{T}_l + (T_1^2 T_2 - T_1 T_2^2) \right] / D$$

$$c_1(\bar{T}_l) = \left[ (T_2 - T_0) \bar{T}_l^2 + (T_0^2 - T_2^2) \bar{T}_l + (T_2^2 T_0 - T_2 T_0^2) \right] / D$$

$$c_2(\overline{T}_l) = \left[ (T_0 - T_1) \overline{T}_l^2 + (T_1^2 - T_0^2) \overline{T}_l + (T_0^2 T_1 - T_0 T_1^2) \right] / D$$

where  $D$  is the common denominator:  $D = T_0^2(T_1 - T_2) + T_1^2(T_2 - T_0) + T_2^2(T_0 - T_1)$

The temperature partials are then

$$\frac{\partial \kappa_{l,m}^{line}}{\partial T_l} = \sum_{i=0}^2 \frac{\partial c_i}{\partial T_l} \kappa_{i,(l,m)} \quad (\text{A.84})$$

where

$$\begin{aligned} \frac{\partial c_0}{\partial T_l} &= \left[ 2(T_1 - T_2) \overline{T}_l + (T_2^2 - T_1^2) \right] / D \\ \frac{\partial c_1}{\partial T_l} &= \left[ 2(T_2 - T_0) \overline{T}_l + (T_0^2 - T_2^2) \right] / D \\ \frac{\partial c_2}{\partial T_l} &= \left[ 2(T_0 - T_1) \overline{T}_l + (T_1^2 - T_0^2) \right] / D \end{aligned} \quad (\text{A.85})$$

#### ***A3.4.5.2 Partial of continuum absorption with respect to temperature*** $\frac{\partial \kappa_{l,m}^{cont}}{\partial T_l}$

For species  $m$ , ( $m = \text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{N}_2$ ,  $\text{O}_2$ ), the CKD v3.0 continuum model (see section 3.3.8.4 and references therein) has tabulated coefficients for use in the following expression for continuum absorption:

$$\kappa_{l,m}^{cont}(\nu, \overline{T}_l, \overline{P}_l) = R(\nu, \overline{T}_l) C_m(\nu, \overline{T}_l, \overline{P}_l) \quad \text{where} \quad R(\nu, \overline{T}_l) = \nu \tanh\left(\frac{hc\nu}{2k_B \overline{T}_l}\right) \quad (\text{A.86})$$

For any  $m$ ,

$$\frac{\partial \kappa_{l,m}^{cont}}{\partial T_l} = \frac{\partial R}{\partial T_l} C_m + R \frac{\partial C_m}{\partial T_l} \quad (\text{A.87})$$

and

$$\frac{\partial R}{\partial T_l} = -\frac{hc}{2k_B \overline{T}_l^2} (R^2 - \nu^2) \quad (\text{A.88})$$

#### ***A3.4.5.2.1 Temperature partials for water vapor continuum coefficient*** $\frac{\partial C_{\text{H}_2\text{O}}}{\partial T_l}$

For  $\text{H}_2\text{O}$ ,  $C_{\text{H}_2\text{O}} = \left( C_S(\overline{T}_l) \overline{q}_l + C_F(1 - \overline{q}_l) \right) \frac{\overline{P}_l}{P_o} \frac{T_o}{\overline{T}_l}$  where  $P_o = 1013 \text{ hPa}$ ,  $T_o = 296 \text{ K}$  and

$$C_S(\overline{T}_l) = C_{S\_296} \left( \frac{C_{S\_260}}{C_{S\_296}} \right)^{T_{fac}} ; T_{fac} = \frac{\overline{T}_l - T_o}{260 - T_o} \text{ with temperature partial}$$

$$\frac{\partial C_{H_2O}}{\partial \overline{T}_l} = -\frac{C_{H_2O}}{\overline{T}_l} + \overline{q}_l \frac{\overline{P}_l}{P_o} \frac{T_o}{\overline{T}_l} \left( \frac{C_S \ln C_S}{260 - T_o} \right) \quad (A.89)$$

**A3.4.5.2.2 Temperature partials for carbon dioxide continuum coefficient**  $\frac{\partial C_{CO_2}}{\partial \overline{T}_l}$

For the CO<sub>2</sub> continuum,  $C_{CO_2} = C_F \frac{\overline{P}_l}{P_o} \frac{T_o}{\overline{T}_l}$  with temperature partial

$$\frac{\partial C_{CO_2}}{\partial \overline{T}_l} = -\frac{C_{CO_2}}{\overline{T}_l} \quad (A.90)$$

**A3.4.5.2.3 Temperature partials for nitrogen continuum coefficient**  $\frac{\partial C_{N_2}}{\partial \overline{T}_l}$

For the N<sub>2</sub> continuum,  $C_{N_2} = C_F \frac{\overline{P}_l}{P_o} \frac{T_o}{\overline{T}_l}$  with temperature partial \

$$\frac{\partial C_{N_2}}{\partial \overline{T}_l} = -\frac{C_{N_2}}{\overline{T}_l} \quad (A.91)$$

**A3.4.5.2.4 Temperature partials for oxygen continuum coefficient**  $\frac{\partial C_{O_2}}{\partial \overline{T}_l}$

For the O<sub>2</sub> continuum,  $C_{O_2} = C_F \frac{\overline{P}_l}{P_o} \exp \left( C_1 (\overline{T}_l - 220) + C_2 (\overline{T}_l - 220)^2 \right)$  with temperature partial

$$\frac{\partial C_{O_2}}{\partial \overline{T}_l} = C_{O_2} [C_1 + 2C_2 (\overline{T}_l - 220)] \quad (A.92)$$

**A3.4.5.3 Partial of layer integrated path amounts with respect to temperature**  $\frac{\partial u_{l,m}}{\partial \overline{T}_l}$

The partial of the radiance with respect to a level temperature depends on the integrated column amounts from layers adjacent to the level:



$$\frac{\partial L}{\partial T_L} = \frac{\partial L}{\partial \tau_{l-1}} \sum_m \kappa_{l-1,m} \frac{\partial u_{l-1,m}}{\partial T_L} + \frac{\partial L}{\partial \tau_l} \sum_m \kappa_{l,m} \frac{\partial u_{l,m}}{\partial T_L} + (\dots), \quad (1.93)$$

where the  $(\dots)$  refers to the other temperature related terms described in this appendix. Unfortunately, this term cannot be explicitly computed layer-by-layer because of the dependence of the layer column amount on the temperature of adjacent levels. However, this term is found to be important (relative to the other components of the temperature Jacobian) only at those levels, particularly the tangent level, where the index of refraction is “large” with peak differences of about 10% between an analytic and finite difference Jacobian. Because optical thickness is also large for those levels with a large index of refraction, we can probably ignore this term. However, we should re-evaluate the decision to ignore this term after the one-day-test if it is found that a significant number of limb retrievals fail due the exclusion of this term in the Jacobian.

### A3.4.6 Layer-to-Level Jacobians

The frequency independent partials that relate layer average quantities to the parameters specified on and retrieved on levels must be computed in the same manner as the layer average quantities in the ray-tracing algorithm. Simpler approximations to this mapping, such as linear-in-log pressure interpolation were found to be unacceptably inaccurate. These jacobians have rather lengthy derivations, which are given in TES Algorithm & Science DFM #217 by H. Worden & S. Sund, July, 2001. Only the results of the derivations will be repeated here. Following equation (A.54), for both limb and nadir cases, we are interested in the following partials:

$$\frac{\partial \ln \bar{q}_{l,m}}{\partial \ln \bar{q}_{L,m}} \text{ and } \frac{\partial \ln \bar{q}_{l,m}}{\partial \ln \bar{q}_{U,m}}; \quad \frac{\partial \bar{T}_l}{\partial T_L} \text{ and } \frac{\partial \bar{T}_l}{\partial T_U}$$

where levels  $L$  (lower) and  $U$  (upper) bound layer  $l$ . For limb cases, path-weighted layer average quantities are computed using a sum over sub-layers, the number and size of which are determined dynamically, with the tangent layer having the most sub-layers. For nadir cases, given our relatively fine forward model pressure grid, it is sufficient to use single layers (*i.e.*, no sub-layers) to compute the path-weighted layer average quantities.

#### A3.4.6.1 Limb layer-to-level VMR Jacobians

The layer vmr,  $\bar{q}_{l,m}$ , for species  $m$  is the integrated species amount divided by the total path amount  $u_l$ :

$$\bar{q}_{l,m} = \frac{H_{\rho,m}}{u_l} \sum_{i=L}^{U-1} \frac{\Delta s_i}{\Delta r_i} (\rho_{i,m} - \rho_{i+1,m}) \quad (A.94)$$

where  $H_{\rho,m}$  is the species density scale height:  $H_{\rho,m} = -\frac{r_U - r_L}{\ln\left(\alpha \frac{q_{U,m}}{q_{L,m}}\right)}$  with

$\alpha = \frac{\rho_U}{\rho_L} = \frac{P_U/T_U}{P_L/T_L}$  and spherical layer upper and lower radii  $r_U$  and  $r_L$ .  $\frac{\Delta S_i}{\Delta r_i}$  is the ratio of line-of-sight distance through sub-layer  $i$  over sub-layer height, and the sub-layer species density is given by:  $\rho_{i,m} = \rho_{L,m} \exp\left(-\frac{r_i - r_L}{H_{\rho,m}}\right)$ .

The layer-to-level VMR jacobians are:

$$\frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_{L,m}} = \frac{H_{\rho,m}}{q_{l,m} u_l} \left[ \sum_{i=L}^{U-1} \frac{\Delta S_i}{\Delta r_i} \left\{ \rho_{i,m} \left( \frac{r_U - r_i}{r_U - r_L} \right) - \rho_{i+1,m} \left( \frac{r_U - r_{i+1}}{r_U - r_L} \right) \right\} \right] + \frac{1}{\ln\left(\alpha \frac{q_{U,m}}{q_{L,m}}\right)} \quad (\text{A.95})$$

$$\frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_{U,m}} = \frac{H_{\rho,m}}{q_{l,m} u_l} \left[ \sum_{i=L}^{U-1} \frac{\Delta S_i}{\Delta r_i} \left\{ \rho_{i,m} \left( \frac{r_i - r_L}{r_U - r_L} \right) - \rho_{i+1,m} \left( \frac{r_{i+1} - r_L}{r_U - r_L} \right) \right\} \right] - \frac{1}{\ln\left(\alpha \frac{q_{U,m}}{q_{L,m}}\right)} \quad (\text{A.96})$$

It is easily verified that equation (A.95) and (A.96) add to 1, which they must in order to

$$\text{have } \bar{q}_{l,m} = \frac{\partial \bar{q}_{l,m}}{\partial q_L} q_L + \frac{\partial \bar{q}_{l,m}}{\partial q_U} q_U = \frac{\bar{q}_{l,m}}{q_L} \left( \frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_L} \right) q_L + \frac{\bar{q}_{l,m}}{q_U} \left( \frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_U} \right) q_U$$

#### A3.4.6.2 Limb layer-to-level Temperature Jacobians

The layer temperature,  $\bar{T}_l$ , is given by:

$$\bar{T}_l = \frac{H_\rho}{u_l} \sum_{i=L}^{U-1} \frac{\Delta S_i}{\Delta r_i} (\rho_i T_i - \rho_{i+1} T_{i+1}) - T_H \quad (\text{A.97})$$

$$\text{where } T_H = H_\rho \left( \frac{T_U - T_L}{r_U - r_L} \right) = -\frac{(T_U - T_L)}{\ln\left(\rho_U/\rho_L\right)},$$

density scale height  $H_\rho = -\frac{r_U - r_L}{\ln\left(\rho_U/\rho_L\right)}$ , sub-layer density is given by  $\rho_i = \rho_L \exp\left(-\frac{r_i - r_L}{H_\rho}\right)$

and sub-layer temperature is given by linear in log pressure interpolation:  $T_i = a + b \ln P_i$

$$\text{with } a = T_L - \frac{\ln P_L}{\ln\left(P_U/P_L\right)} (T_U - T_L) \text{ and } b = \frac{T_U - T_L}{\ln\left(P_U/P_L\right)}.$$

The layer-to-level temperature jacobians are:

$$\begin{aligned} \frac{\partial \bar{T}_l}{\partial T_L} = & \frac{H_\rho}{u_l T_L} \sum_{i=L}^{U-1} \frac{\Delta s_i}{\Delta r_i} \left\{ \rho_i \left( \frac{r_U - r_i}{r_U - r_L} \right) (\bar{T}_l - T_H + T_L - T_i) - \rho_{i+1} \left( \frac{r_U - r_{i+1}}{r_U - r_L} \right) (\bar{T}_l - T_H + T_L - T_{i+1}) \right\} \\ & - \frac{H_\rho}{r_U - r_L} \left( 1 - \frac{T_H}{T_L} \right) \end{aligned} \quad (\text{A.98})$$

$$\begin{aligned} \frac{\partial \bar{T}_l}{\partial T_U} = & \frac{H_\rho}{u_l T_U} \sum_{i=L}^{U-1} \frac{\Delta s_i}{\Delta r_i} \left\{ \rho_i \left( \frac{r_U - r_i}{r_U - r_L} \right) (\bar{T}_l - T_H + T_U - T_i) - \rho_{i+1} \left( \frac{r_U - r_{i+1}}{r_U - r_L} \right) (\bar{T}_l - T_H + T_U - T_{i+1}) \right\} \\ & + \frac{H_\rho}{r_U - r_L} \left( 1 - \frac{T_H}{T_U} \right) \end{aligned} \quad (\text{A.99})$$

#### A3.4.6.3 Nadir layer-to-level VMR Jacobians

When sub-layers are not applied, the layer average quantities reduce to simpler expressions. We then have layer-to-level VMR jacobians:

$$\frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_{L,m}} = \frac{q_{L,m}}{q_{L,m} - \alpha q_{U,m}} + \frac{1}{\ln \left( \alpha \frac{q_{U,m}}{q_{L,m}} \right)} \quad (\text{A.100})$$

$$\frac{\partial \ln \bar{q}_{l,m}}{\partial \ln q_{U,m}} = \frac{-\alpha q_{U,m}}{q_{L,m} - \alpha q_{U,m}} - \frac{1}{\ln \left( \alpha \frac{q_{U,m}}{q_{L,m}} \right)} \quad (\text{A.101})$$

#### A3.4.6.4 Nadir layer-to-level Temperature Jacobians

Likewise, the layer average temperature expression becomes simpler and the layer-to-level temperature jacobians are:

$$\frac{\partial \bar{T}_l}{\partial T_L} = \frac{\bar{T}_l - T_H}{T_L} \left( \frac{\rho_L}{\rho_L - \rho_U} \right) + \frac{1}{\ln \left( \rho_U / \rho_L \right)} \left( 1 - \frac{T_H}{T_L} \right) \quad (\text{A.102})$$

$$\frac{\partial \bar{T}_l}{\partial T_U} = \frac{\bar{T}_l - T_H}{T_U} \left( \frac{-\rho_U}{\rho_L - \rho_U} \right) - \frac{1}{\ln \left( \rho_U / \rho_L \right)} \left( 1 - \frac{T_H}{T_U} \right) \quad (\text{A.103})$$

$$\text{where } T_H = - \frac{(T_U - T_L)}{\ln \left( \rho_U / \rho_L \right)}$$

#### A3.4.7 Pointing Jacobians

The field of view integration for the radiance measured with detector  $d$ , from section 3.3.6 is given by

$$L_{sat}(\theta_d) = \sum_{j=0}^{N_{FOV}} L(\theta_j) \mathbf{R}_{FOV}(\theta_j - \theta_d) \Delta\theta_j \quad (\text{A.104})$$

Writing this as an integral,

$$L_{sat}(\theta_d) = \int_{\theta_{\min}}^{\theta_{\max}} L(\theta) \mathbf{R}_{FOV}(\theta - \theta_d) d\theta \quad (\text{A.105})$$

Since  $\frac{\partial \mathbf{R}_{FOV}}{\partial \theta_d} = -\frac{\partial \mathbf{R}_{FOV}}{\partial \theta}$ , we have

$$\frac{\partial L_{sat}}{\partial \theta_d} = \int_{\theta_{\min}}^{\theta_{\max}} L(\theta) \left( -\frac{\partial \mathbf{R}_{FOV}}{\partial \theta} \right) d\theta \quad (\text{A.106})$$

Integration by parts gives

$$\frac{\partial L_{sat}}{\partial \theta_d} = -L(\theta) \mathbf{R}_{FOV}(\theta - \theta_d) \Big|_{\theta_{\min}}^{\theta_{\max}} + \int_{\theta_{\min}}^{\theta_{\max}} \left( \frac{\partial L}{\partial \theta} \right) \mathbf{R}_{FOV}(\theta - \theta_d) d\theta \quad (\text{A.107})$$

Assuming we have chosen  $\theta_{\min}$  and  $\theta_{\max}$  to be angles where the detector response is negligible, the first term in equation (A.107) is zero. This leaves the second term, which we write as a sum:

$$\frac{\partial L_{sat}}{\partial \theta_d} = \sum_{j=0}^{N_{FOV}} \left( \frac{\partial L}{\partial \theta_j} \right) \mathbf{R}_{FOV}(\theta_j - \theta_d) \Delta\theta_j \quad (\text{A.108})$$

This now has the same form as equation (A.104) with  $L(\theta_j)$  replaced by  $\frac{\partial L}{\partial \theta_j}$ . The  $\frac{\partial L_{sat}}{\partial \theta_d}$  partials are then computed in the same way we compute detector radiances, with the switch to ray indices as described in section 3.3.6.

For 4-point Lagrange interpolation,  $L(\theta_j) = \sum_{m=-1}^2 a_{j,m} L(\theta_{k+m})$  and we have

$$\frac{\partial L}{\partial \theta_j} = \sum_{m=-1}^2 \frac{\partial a_{j,m}}{\partial \theta_j} L(\theta_{k+m}) \quad (\text{A.109})$$

Since the interpolation coefficients are defined with respect to the variable  $p$ , with

$$p = \frac{\theta_j - \theta_k}{\theta_{k+1} - \theta_k}, \text{ we have}$$

$$\frac{\partial a_{j,m}}{\partial \theta_j} = \frac{\partial a_{j,m}}{\partial p} \frac{\partial p}{\partial \theta_j} = \frac{\partial a_{j,m}}{\partial p} \left( \frac{1}{\theta_{k+1} - \theta_k} \right) \quad (\text{A.110})$$

where

$$\begin{aligned} \frac{\partial a_{j,-1}}{\partial p} &= (-1 + 4p - 3p^2) / (1 + c_1) \\ \frac{\partial a_{j,0}}{\partial p} &= 6p(p-1) + p(2-3p) / (1 + c_2) \\ \frac{\partial a_{j,1}}{\partial p} &= 6p(1-p) + (1-4p+3p^2) / (1 + c_1) \\ \frac{\partial a_{j,2}}{\partial p} &= (3p^2 - 2p) / (1 + c_2) \end{aligned} \quad (\text{A.111})$$

with  $c_1 = (\theta_k - \theta_{k-1}) / (\theta_{k+1} - \theta_k)$  and  $c_2 = (\theta_{k+2} - \theta_{k+1}) / (\theta_{k+1} - \theta_k)$ .

As noted above, these partials of the interpolation coefficients are then propagated along with the interpolation coefficients to obtain both detector radiances and pointing jacobians.

### A3.4.8 Jacobian Validation

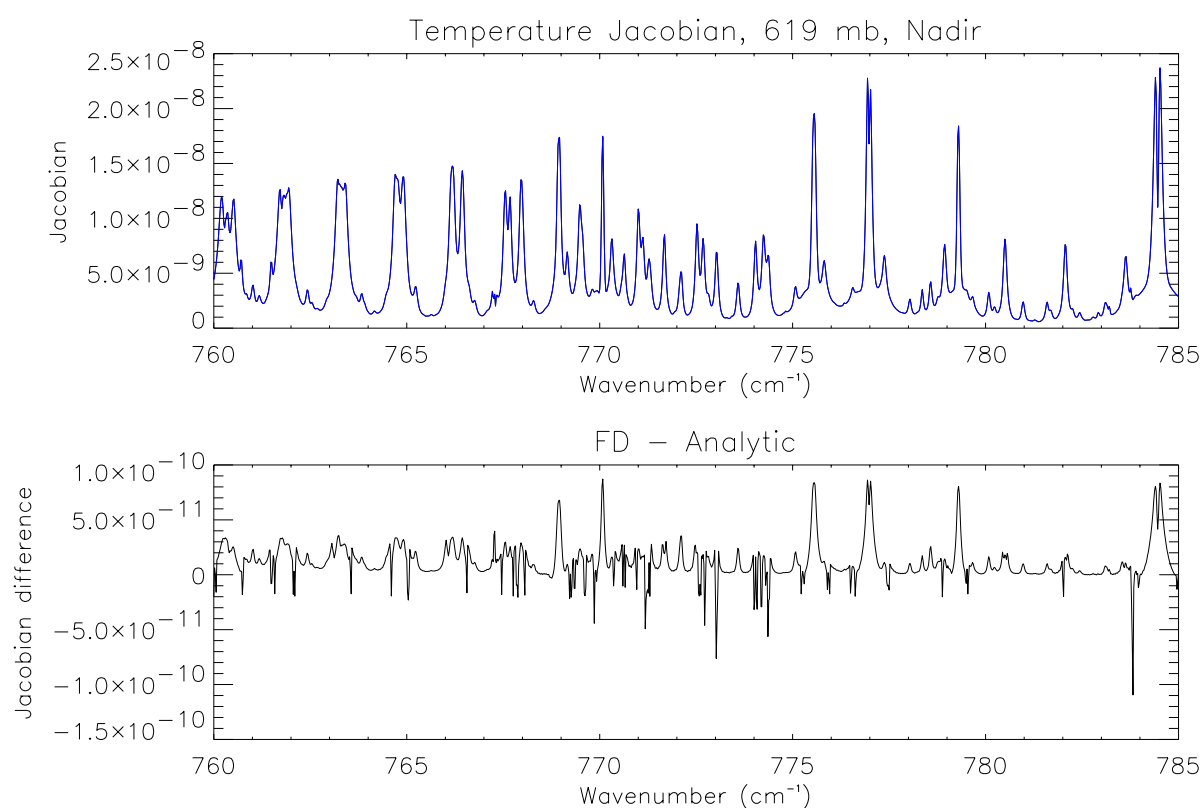
We validate our analytic jacobians by comparing to jacobians computed by the finite difference (FD) method described in section 3.4.1.

#### A3.4.8.1 Nadir Jacobian Validation

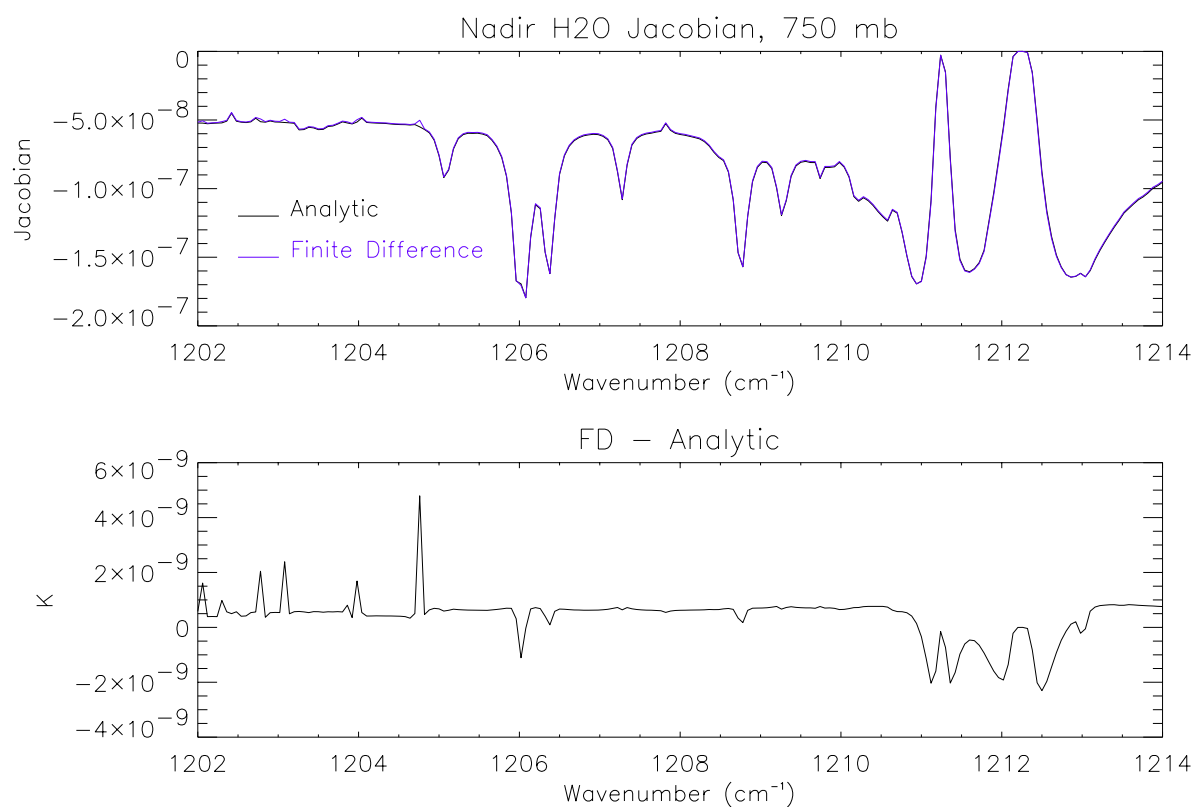
**Table A-3: Nadir jacobian comparisons: Finite Difference (FD) to Analytic**

Retrieved Parameter	Frequency Range (cm <sup>-1</sup> )	Max FD value	Max  FD-Analytic	RMS  FD-Analytic
Temperature at 619 mb	760-785	2.37e-08	1.1e-10	2.0e-11
H <sub>2</sub> O at 750 mb	1202-1214	1.80e-07	4.8e-09	8.7e-10

**Figure A-10:**



**Figure A-11:**

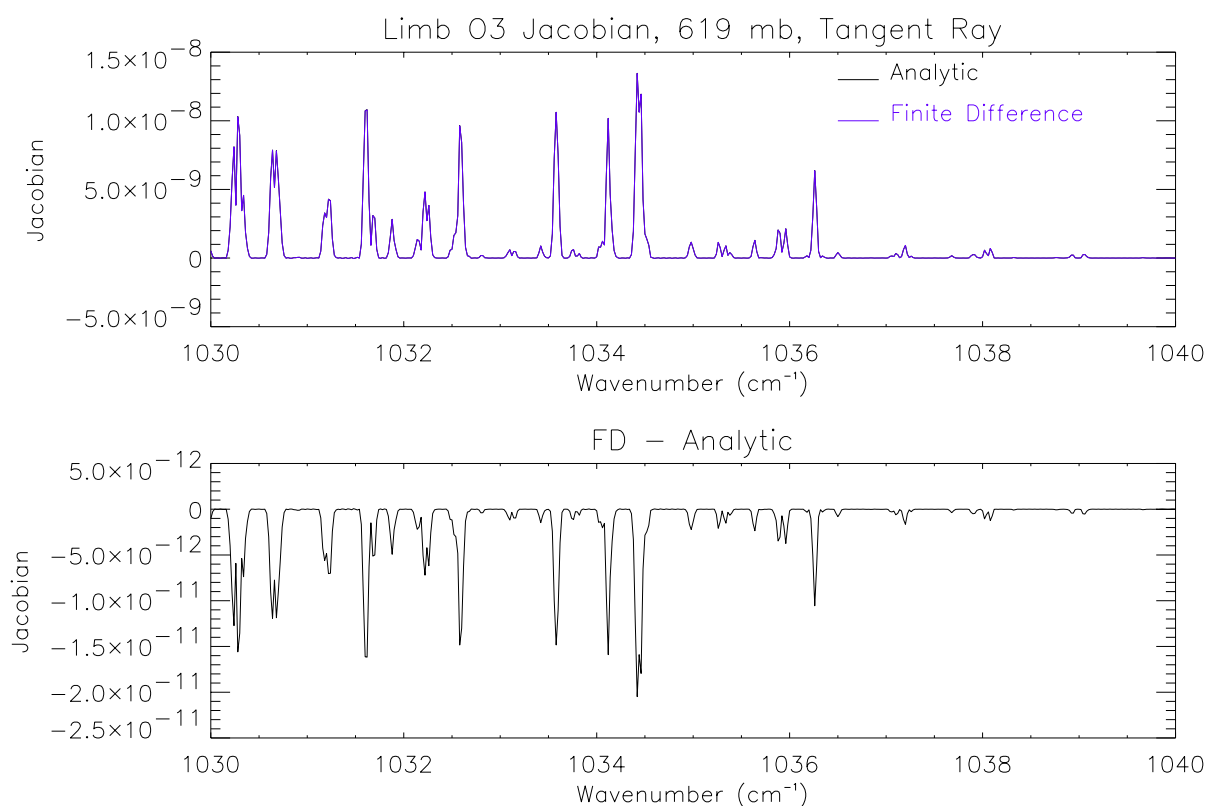


#### A3.4.8.2 Limb Jacobian Validation

**TableA- 4: Limb jacobian comparisons: Finite Difference (FD) to Analytic**

Retrieved Parameter	Frequency Range (cm <sup>-1</sup> )	Limb Ray Tangent Pressure	Max FD value	Max  FD-Analytic	RMS  FD-Analytic
O <sub>3</sub> at 619 mb	1030-1040	1000 mb	2.71e-08	3.6e-11	6.4e-12
		909 mb	2.47e-08	3.0e-11	5.6e-12
		825 mb	2.20e-08	2.1e-11	4.6e-12
		750 mb	1.78e-08	1.7e-11	3.8e-12
		681 mb	6.79e-09	6.0e-12	1.2e-12
		619 mb	1.34e-08	2.0e-11	3.3e-12
H <sub>2</sub> O at 750 mb	1204-1214	1000 mb	2.06e-07	1.2e-09	5.8e-10
		909 mb	2.02e-07	3.3e-10	1.3e-10
		825 mb	1.08e-07	1.7e-10	1.0e-10
		750 mb	4.61e-07	6.4e-10	2.2e-10

**Figure A-12:**



### A3.5.1 Retrieval Strategy

This appendix gives descriptions of the retrieval strategy suppliers listed in section 3.5.1.2 and 3.5.1.3.

#### Target level suppliers:

##### *Strategy Table.*

Strategy table parameters are read and organized so to make the strategy table information is easily accessible by the other suppliers. The strategy table contains information about the retrieval steps to perform, controlling parameters, and the locations of the OSPs to use for the various data.

##### *Surface pressure.*

The surface pressure is calculated at the surface altitude (an input from Geolocation) using the hydrostatic equation with the sea surface pressure (from metrology data), lowest atmospheric temperature (from metrology data), and lowest atmospheric water value (from metrology data).



### *BT*

If the level 1b cloud flag indicates low intrapixel variability, the scene may be either uniformly cloud free or cloud filled. To distinguish between cloud free or cloud filled, the difference between the observed radiance and the radiance calculated at the initial guess between 867 cm<sup>-1</sup> and 898 cm<sup>-1</sup>. (1) If this difference is small, the scene is considered clear and processing continues. (2) If this difference is large and the intrapixel variability of BT11 is low, this will be identified as a retrievable cloud filled scene. The cloud height and optical depth will be retrieved in the first steps of the retrieval.

### *Forward model pressure.*

Once the surface pressure has been determined, the FMPressure vector is created starting from the standard pressure grid: (1) Cut off the levels below the surface pressure on the standard pressure grid. (2) Add a level at the surface pressure. (3) Possibly remove the pressures adjacent to the surface pressure if they are too close (the current cutoff is 0.1%).

### *Target level full state vector (initial guess).*

The information for the initial state vector is gathered as described in section 3.2.2. For each species, use one or multiple sources (specified in the strategy table) to create a single profile. For an atmospheric species: (1) interpolate from the pressure levels of the sources to FMPressures. (2) If the control parameter specifies it, project the initial guess to within the span of the retrieval vector using the maps created in the map supplier. (3) Also, eventually have the capability of creating hybrid profiles using meteorological data and other specified parameters, for example interpolate from a profile to the meteorologically specified surface value, if this is needed.

### *True full state vector.*

This is only used for data simulation and error analysis of simulated data. The true full state needs all of the functionality of the Sequence Level Full State Vector and can use the same class as the Sequence Level Full State Vector, but with different sources provided by the strategy table. This describes the true state used to simulate an observed radiance.

### *Target level emissivity.*

This supplier creates a vector of emissivity vs. frequency using (1) the land cover database to determine the land cover types and amount of each type in the target scene footprint, and (2) the emissivities for the different land cover types.

### *Target level map.*

This supplier creates maps from retrieval parameters to forward model levels and vice versa. (see section 3.5.2.1). This may use retrieval levels sub-supplier to get the retrieval levels on the FMPressures grid, or it may read in the map and inverse map. If maps are read in, they will be on the standard pressure grid and must be modified to the FMPressures grid. Although conceptually this is a step-level supplier, the maps are needed for projecting the initial guess before the first step. See section 3.5.2.1 for a more detailed description of mapping.

*Simulated spectrum.*

Simulates radiance data using the true state. This is only used for data simulation. The output data is formatted exactly like real data and can have noise added or be noiseless.

*Measured spectrum.*

This supplier (1) averages spectra information (for both good scans and good pixels, in nadir mode), (2) RMS the noise over pixels and scans (for both good scans and good pixels, in nadir mode), (3) apodizes the spectra, (4) apodizes the NESR. This is equivalent to multiplying the NESR by a factor. The factors are:

	nadir	limb
Norton-Beer weak	0.738	0.8177
Norton-Beer moderate	0.665	0.7590
Norton-Beer strong	0.611	0.8177

*Target level Microwindows definitions.*

This supplier selects the correct list of microwindows for each retrieval step or combined microwindows for all steps. The microwindows are selected using the list of retrieval species for that step, the steptype (e.g. retrieval, simulation, or BT) and view mode (nadir or limb). For each microwindow, it also gets the list of forward model species, filter, and detector mask (occupation matrix). Although conceptually this is a step-level supplier, all the microwindows are needed upfront if the PGE is run in data-simulating mode.

**Step level suppliers:**

*Step level map.*

Get maps for this step for all atmospheric species from the Target Level Map Supplier.

*Step level Microwindows definitions.*

Get relevant information from Target Level Microwindows Definitions Supplier for this step.

*A priori  $x_a$ .*

This supplier has the same requirements as the Target level full state supplier, with different source instances. It must also map to the retrieval parameters in the case of an atmospheric species. It must get have access to non-atmospheric state parameters that are retrieved (e.g. pointing angle, surface temperature, and emissivity).

*A priori constraint.*

Create the full constraint matrix (which is square with dimension = # retrieval parameters) as described in section 3.5.3.

*A priori climatology covariance.*

Create the full covariance matrix (which is square with dimension = # retrieval parameters) to be used in error analysis as described in section 3.5.9.

*Microwindows radiances.*

Pick out the radiances in the given microwindows. Use the noise vector to deweight particular frequencies with the occupation matrix. Provides the radiances and noise for the retrieval microwindows in this step. This supplier must also provide a flat array with all spikes regions and all bad pixels removed for the NESR and radiance to be used in error analysis.

*Emissivity a priori.*

This supplier selects the emissivity retrieval frequencies based on the microwindow information, using the target level emissivity output, and control parameters. It also creates the constraint matrix and true covariance for emissivity similarly to the other constraint matrices. Its output is the a priori vector and constraint for emissivity.

*Step level full state vector.*

This supplier gets the information from the updated target level full state vector needed for the step level full state vector.

*Retrieval levels.*

This supplier gets the retrieval levels for a particular retrieval species and viewmode (nadir or limb) and matype (linear or log). The retrieval levels in the OSP's are associated with the pressures in StandardPressureLevels and must be adjusted to the FMPressures by the following steps:

- (1) Remove levels outside of FMPressures.
- (2) Reindex levels so that the level corresponding to the lowest FMPressures is level 1.
- (3) Add or move levels so that there is always a retrieval level associated with the lowest and highest FMPressures. There is a threshold for when to add a new level versus move an existing level.

**A3.5.3.2 Mapping FSV to Retrieval Vector and vice versa**

The role of mapping is to connect parameters distinguishable within the resolution and sensitivity of the observations to quantities used in the higher precision calculation of the forward model and jacobians. Mapping has been implemented in the production software so as to allow for great flexibility. Retrieval parameters related to atmospheric species can be specified either directly in linear combinations of volume mixing ratio (vmr) or in linear combinations of  $\ln(\text{vmr})$ . Mapping has been implemented to allow expression of the jacobians in either derivatives of vmr or  $\ln(\text{vmr})$ . Mapping has been implemented to allow interpolation across forward model pressure either linearly in pressure (with retrieval parameters expressed in vmr) or linearly in  $\ln(\text{pressure})$ . Table 3.2.4A-1 shows the options for mapping implemented in the production code. Note that shape retrieval, which is retrieval of VMR with respect to pressure and retrieval of atmospheric temperature (TATM) are the two types in which quantities

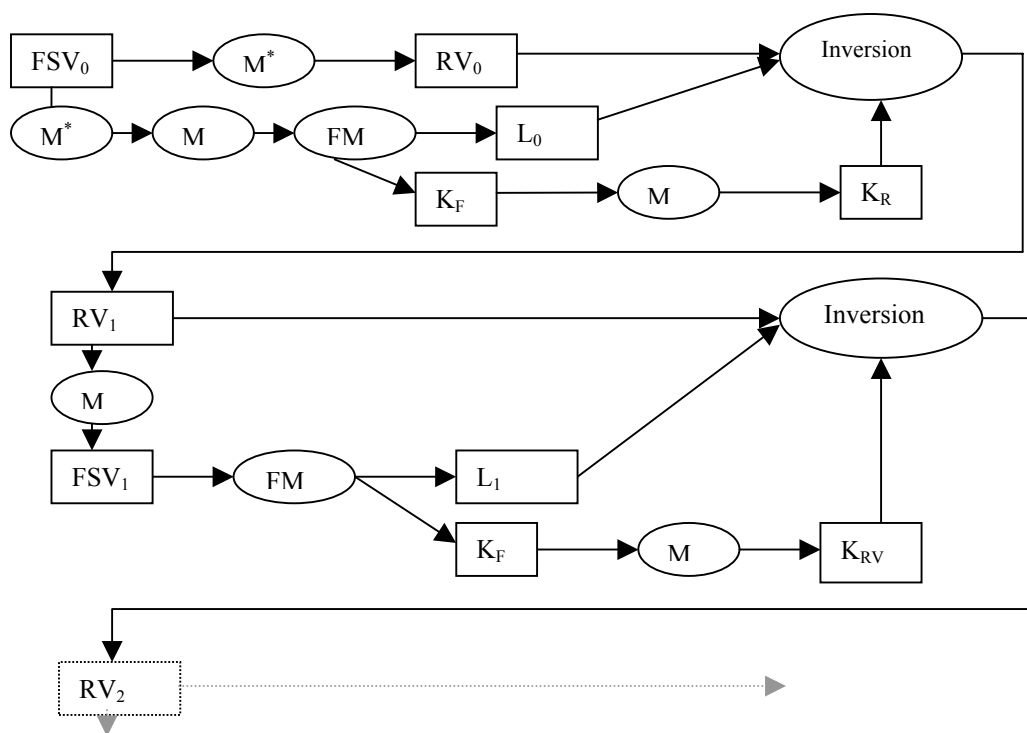
are expressed uniformly. Everything else is a mixture of log of the quantity and the quantity itself.

**Table 5: Retrieval/Map Options**

Retrieval Type	FSV	RV	Ret.Quantity	Mapped	Jacobian
Ret. Levels	VMR	VMR	VMR	ln(VMR)	ln(VMR)
SHAPE_RET.	VMR	VMR	VMR	VMR	VMR
Ln(VMR)	VMR	ln(VMR)	ln(VMR)	ln(VMR)	ln(VMR)
TATM	TATM	TATM	TATM	TATM	TATM

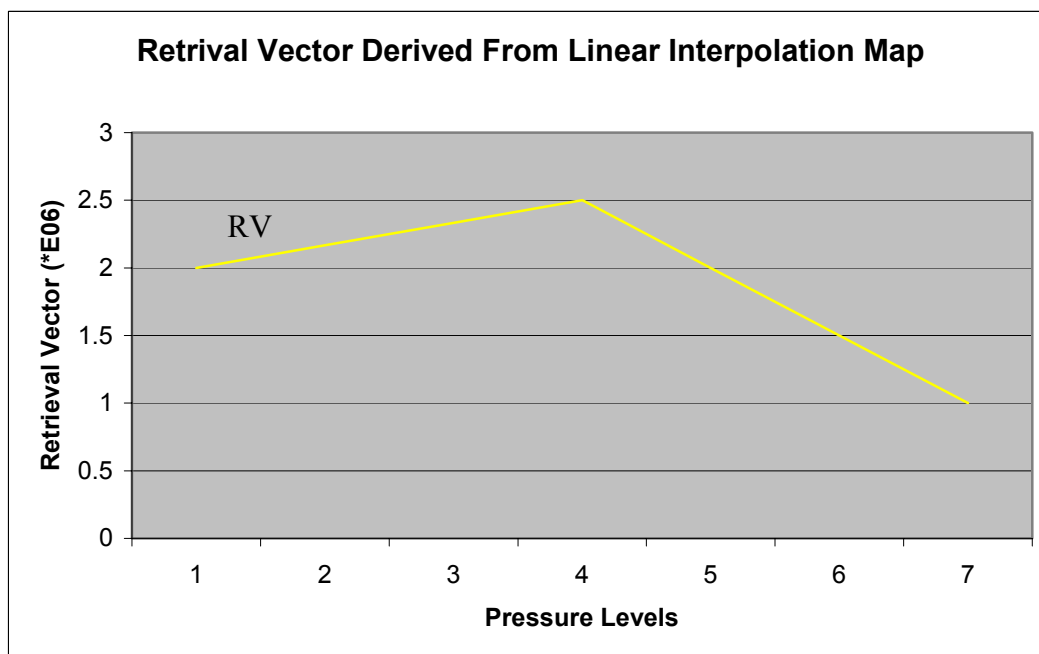
Maps from the Full State Vector to the Retrieval Vector are used to initialize the retrieval parameters. This is done at the beginning of the nonlinear least squares iterative process. After that updates to the FSV are done with maps from the Retrieval Vector. Jacobians derived on the full pressure grid use the FSV update map as well. Below is a diagram of the iterative relationship between the Full State Vector (FSV), Retrieval Vector (RV), Map (M), Inverse Map (M\*), Radiance (L), FSV Jacobian ( $K_{FSV}$ ), RV Jacobian ( $K_{RV}$ ), and Inversion, projecting FSV.

Figure 13: Iterative Inversion Process for L2



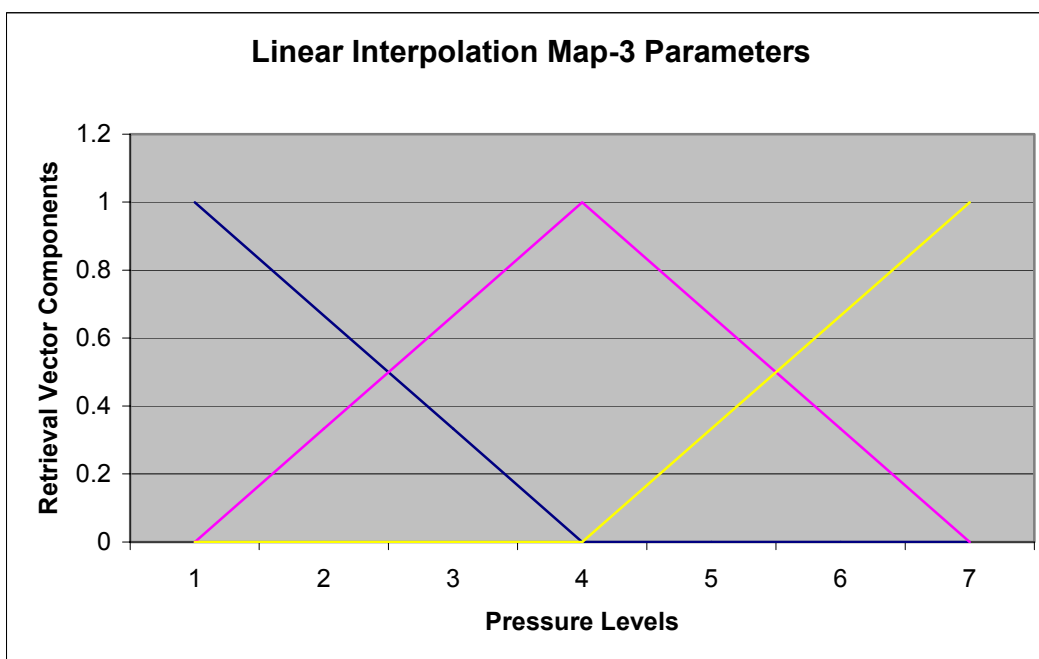
Below are two examples of mapping used: A standard retrieval level map, 3 parameters over 7 levels and a shape retrieval over 85 levels. First is a standard vmr profile plot based showing the retrieval vector across the forward model pressure levels. The three retrieval level vmr's being retrieved – the 3 parameters, are the coefficients used to multiply the component vectors.

Figure 14: Retrieval vector derived from linear interpolation map.



This retrieval vector is based on three component vectors, as seen in the next figure.

Figure 15: Linear interpolation map – 3 parameters



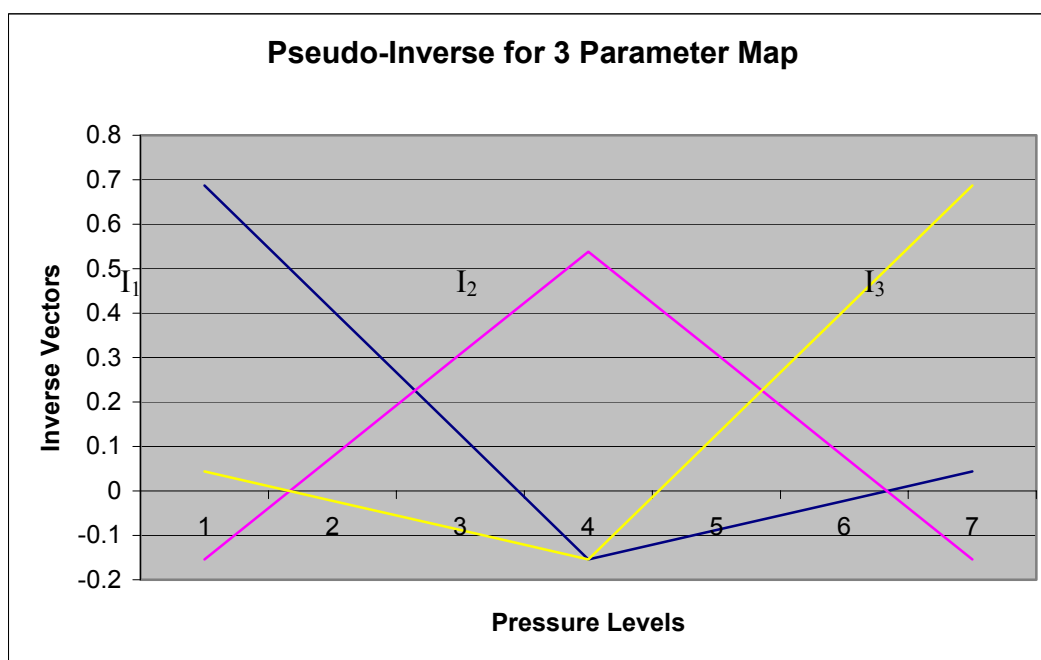
**Table 6: Retrieval vectors for 3 a parameter interpolation map**

$R_1 =$	$R_2 =$	$R_3 =$
1	0	0
0.66665	0.33335	0
0.33333	0.66667	0

The coefficients multiplying the components are 2.0E-06, 2.5E-06, and 1.0E-06 respectively; these coefficients are also the retrieval parameters. A quick check can show that  $RV = 2e-6 \cdot R_1 + 2.5e-6 \cdot R_2 + 1e-6 \cdot R_3$ .

The matrix used to initialize the retrieval parameters for RV is based on the three components of the pseudo-inverse.

**Figure 16: Psueudo-Inverse for 3 parameter map**



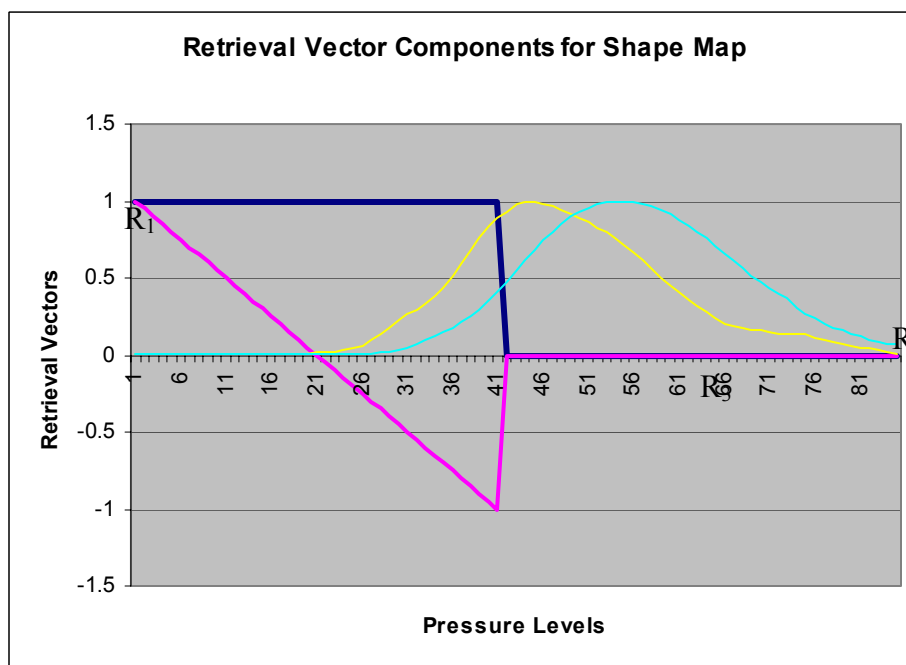
**Table 7: Inverse Vectors for 3 Parameter Interpolation Map**

$I_1 =$	$I_2 =$	$I_3 =$
0.68682	-0.1538	0.04396
0.40659	0.07693	-0.022
0.12637	0.30769	-0.0879
-0.1538	0.53846	-0.1538
-0.0879	0.30769	0.12638
-0.022	0.07692	0.40659
0.04396	-0.1538	0.68681

### A3.5.3.2.1 Shape Retrieval Map

The shape retrieval map is also composed of component vectors. The simplest shape retrieval map used has 4 retrieval parameters, the amplitude coefficients of the vectors in the figure below.

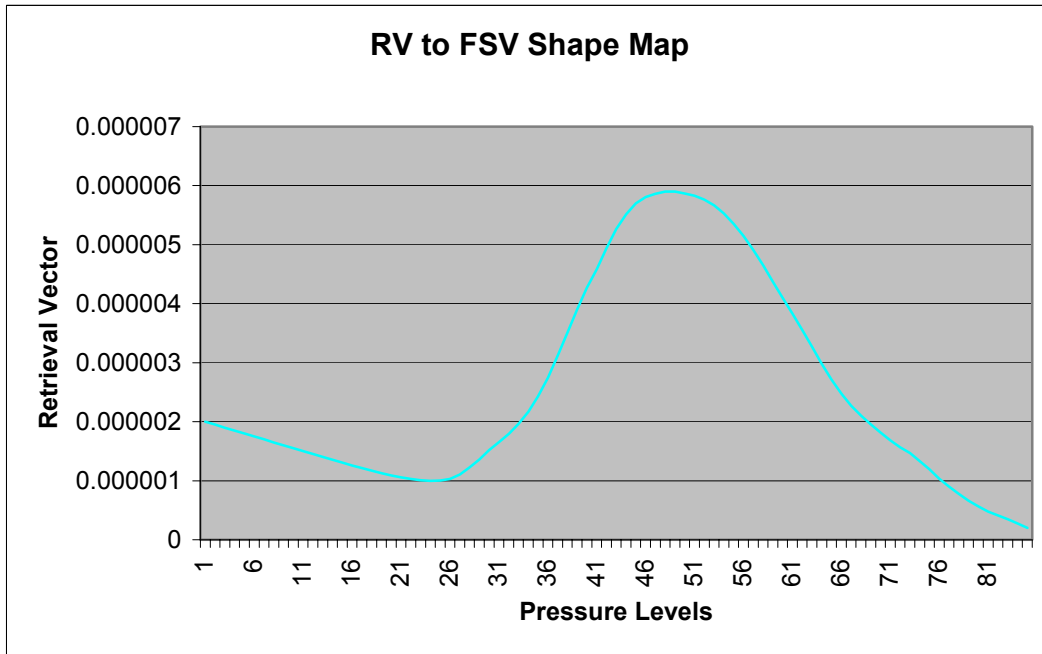
**Figure 17: Retrieval vector components for shape map.**



These retrieval vectors can be interpreted physically, similarly to retrieval levels.  $R_1$  corresponds to the average vmr of the troposphere – the troposphere column amount.  $R_2$  corresponds to a linear dropoff of the tropospheric component of the vmr.  $R_3$  and  $R_4$  are stratospheric components which assume the climatologically derived  $O_3$  vmr, increasing to a peak in the stratosphere and then smoothly decreasing. With initial amplitudes of  $1e-6$ ,  $1e-6$ ,  $4e-6$ , and  $2.5e-6$  respectively, the total initial profile – the initial retrieval vector (RV) is given in Figure

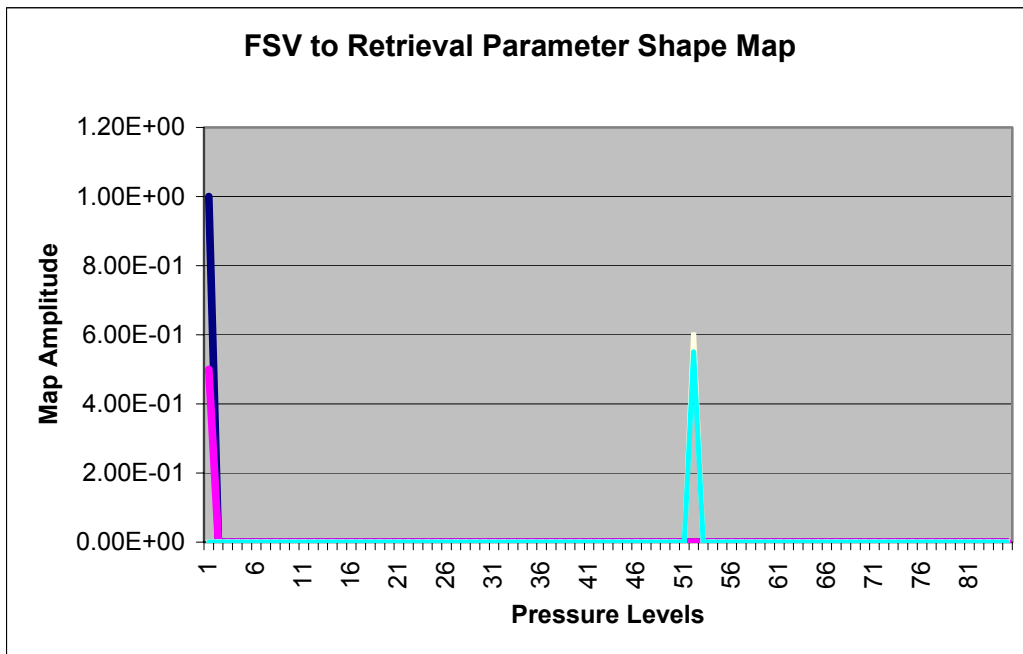


Figure 18: RV to FSV shape map.



Finally, the inverse map is given by the inverse shape vectors as shown in Figure.

Figure 19:



These vectors are based a simpler algorithm than the pseudo-inverse vectors used for the initialization of retrieval level parameters. The coefficients were picked by inspection,

specifically to yield the desired initialization coefficients based on values from only 2 of the 85 forward model pressure levels that the full state vector contains: Level 1 and level 51. The value from level 1 is used to scale the tropospheric components of the RV, the value from 51 the stratospheric RV components. Table 3.2.4A-2 and table 3.2.4A-3 give the complete set of values for both the RV and inverse vector components for the shape map.

**Table 8: Retrieval vectors to 4 parameter shape map**

1000.00	1.00000	1.00000	1.63256e-06	1.49157e-07
908.514	1.00000	0.950000	2.74838e-06	2.51103E-07
825.402	1.00000	0.900000	4.68906e-06	4.19815e-07
749.893	1.00000	0.850000	7.96203E-06	6.97931e-07
681.291	1.00000	0.800000	1.32099e-05	1.15195e-06
618.966	1.00000	0.750000	2.16465e-05	1.91154e-06
562.342	1.00000	0.700000	3.58487e-05	3.14956e-06
510.898	1.00000	0.650000	5.80688e-05	5.09690e-06
464.160	1.00000	0.600000	9.30202E-05	8.16575e-06
421.698	1.00000	0.550000	0.000150751	1.31337e-05
383.117	1.00000	0.500000	0.000236407	2.09114e-05
348.069	1.00000	0.450000	0.000370593	3.28307e-05
316.227	1.00000	0.400000	0.000581728	5.15302E-05
287.298	1.00000	0.350000	0.000887136	8.03224e-05
261.016	1.00000	0.300000	0.00138280	0.000122985
237.137	1.00000	0.250000	0.00207467	0.000188056
215.444	1.00000	0.200000	0.00311635	0.000286387
195.735	1.00000	0.150000	0.00456237	0.000428448
177.829	1.00000	0.100000	0.00667176	0.000648630
161.561	1.00000	0.0500000	0.00963030	0.000952442
146.779	1.00000	0.000000	0.0135096	0.00139914
133.352	1.00000	-0.0500000	0.0187720	0.00201321
121.152	1.00000	-0.100000	0.0253665	0.00289039
110.069	1.00000	-0.150000	0.0344652	0.00412180
100.000	1.00000	-0.200000	0.0465288	0.00582480
90.8518	1.00000	-0.250000	0.0645052	0.00820241
82.5406	1.00000	-0.300000	0.0948668	0.0115088
74.9896	1.00000	-0.350000	0.133287	0.0161565
68.1295	1.00000	-0.400000	0.176483	0.0226320
61.8963	1.00000	-0.450000	0.222105	0.0318617
56.2339	1.00000	-0.500000	0.259978	0.0464488
51.0896	1.00000	-0.550000	0.293797	0.0670764
46.4158	1.00000	-0.600000	0.333360	0.0919554
42.1696	1.00000	-0.650000	0.379833	0.120073
38.3119	1.00000	-0.700000	0.439606	0.148565
34.8071	1.00000	-0.750000	0.512288	0.178205
31.6229	1.00000	-0.800000	0.595726	0.212511
28.7299	1.00000	-0.850000	0.681056	0.252097

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26.1017	1.00000	-0.900000	0.764106	0.298235
23.7136	1.00000	-0.950000	0.834524	0.351409
21.5443	1.00000	-1.00000	0.887771	0.412789
19.5734	0.00000	0.00000	0.934659	0.478535
17.7828	0.00000	0.00000	0.974742	0.547283
16.1560	0.00000	0.00000	0.995026	0.614466
14.6780	0.00000	0.00000	1.00000	0.679116
13.3352	0.00000	0.00000	0.986947	0.743340
12.1153	0.00000	0.00000	0.962265	0.804897
11.0070	0.00000	0.00000	0.939293	0.856290
10.0000	0.00000	0.00000	0.913440	0.898763
9.08514	0.00000	0.00000	0.884329	0.932729
8.25402	0.00000	0.00000	0.857529	0.959541
7.49893	0.00000	0.00000	0.829033	0.979588
6.81291	0.00000	0.00000	0.796152	0.992072
6.18966	0.00000	0.00000	0.758519	0.998225
5.62342	0.00000	0.00000	0.713267	1.00000
5.10898	0.00000	0.00000	0.663909	0.995752
4.64160	0.00000	0.00000	0.612326	0.984696
4.21698	0.00000	0.00000	0.559124	0.967309
3.83117	0.00000	0.00000	0.504544	0.943821
3.48069	0.00000	0.00000	0.453752	0.914693
3.16227	0.00000	0.00000	0.407093	0.880282
2.87298	0.00000	0.00000	0.362963	0.841129
2.61016	0.00000	0.00000	0.318358	0.798776
2.37137	0.00000	0.00000	0.274467	0.754751
2.15443	0.00000	0.00000	0.235093	0.709058
1.95734	0.00000	0.00000	0.204496	0.661392
1.77828	0.00000	0.00000	0.185394	0.612405
1.61560	0.00000	0.00000	0.174004	0.563793
1.46780	0.00000	0.00000	0.165535	0.517468
1.33352	0.00000	0.00000	0.157038	0.475229
1.21153	0.00000	0.00000	0.148003	0.437251
1.10069	0.00000	0.00000	0.140352	0.402084
1.00000	0.00000	0.00000	0.137057	0.368684
0.825404	0.00000	0.00000	0.138893	0.310539
0.681290	0.00000	0.00000	0.130719	0.268085
0.562340	0.00000	0.00000	0.112819	0.234766
0.464160	0.00000	0.00000	0.0965203	0.205877
0.383120	0.00000	0.00000	0.0813771	0.180034
0.316230	0.00000	0.00000	0.0670186	0.157233
0.261020	0.00000	0.00000	0.0548975	0.136703
0.215440	0.00000	0.00000	0.0457406	0.118081
0.177830	0.00000	0.00000	0.0394382	0.101659
0.146780	0.00000	0.00000	0.0321292	0.0879014

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0.121150	0.00000	0.00000	0.0210628	0.0763964
0.100000	0.00000	0.00000	0.00913862	0.0657701

**Table 9: Inverse vectors for 4 parameter shape map**

1.00000E+03	1.0000E+00	0.5000E+00	0.0000E+00	0.0000E+00
9.08514E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8.25402E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7.49893E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.81291E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.18966E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.62342E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.10898E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.64160E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.21698E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.83117E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.48069E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.16227E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.87298E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.61016E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.37137E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.15444E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.95735E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.77829E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.61561E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.46779E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.33352E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.21152E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.10069E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.00000E+02	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9.08518E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8.25406E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7.49896E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.81295E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.18963E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.62339E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.10896E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.64158E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.21696E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.83119E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.48071E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.16229E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.87299E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.61017E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.37136E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.15443E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

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1.95734E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.77828E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.61560E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.46780E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.33352E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.21153E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.10070E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.00000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9.08514E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8.25402E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7.49893E+00	0.0000E+00	0.0000E+00	5.9876E-01	5.4969E-01
6.81291E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.18966E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.62342E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.10898E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.64160E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.21698E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.83117E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.48069E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.16227E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.87298E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.61016E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.37137E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.15443E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.95734E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.77828E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.61560E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.46780E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.33352E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.21153E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.10069E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.00000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8.25404E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6.81292E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5.62341E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4.64159E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.83118E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3.16229E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.61017E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
2.15443E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.77828E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.46780E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.21153E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
1.00000E-01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

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